ChEESE

www.cheese-coe-eu

Center of Excellence for Exascale in Solid Earth

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

SeisSol training

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github.com/SeisSol

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Welcome!

We will cover **three SeisSol applications**::

- using a **kinematic earthquake** source model of the 1994 Northridge earthquake in a standard format and model ground motions
- a **3D dipping fault dynamic rupture** with **off-fault plastic deformation based** on a USGS/SCEC community benchmark problem (e.g., Harris et al., 2018)
- a 3D complex dynamic rupture earthquake scenario of the **2018, Palu, Sulawesi supershear earthquake**

but first we setup the Docker container uphoffc/seissol-training

What is inside the Docker container?

The Docker container contains the pre-installed tools we need for the workshop in order to create a point source file and to create a mesh. (rconv/gmsh/pumgen)

You did install Docker, right?

on your desktop/laptop: Docker setup

Please open a terminal (Windows: PowerShell) and run (right now)

```
$ docker pull uphoffc/seissol-training
> docker pull uphoffc/seissol-training
```

Note: **$** Linux/Mac, **>** Windows, **$/>** all systems

training agenda

main zoom room: introduction

breakout rooms (6): hands-on computing on the cluster and on your desktop/laptop using docker for each participant
main zoom room: discussion of each example

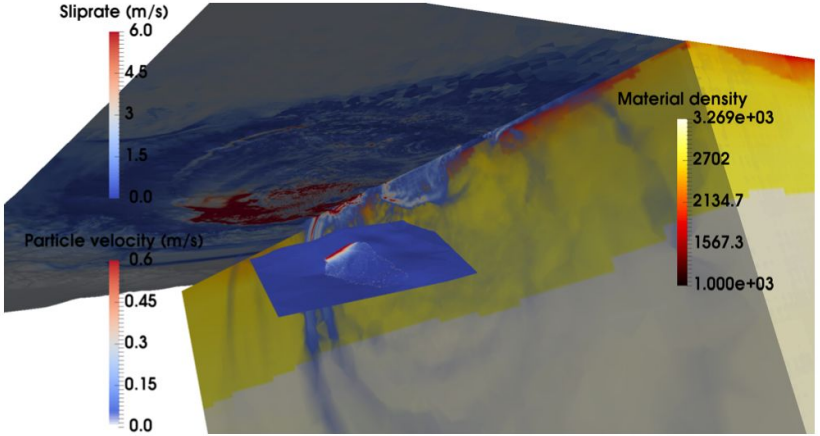
as a **backup** we pre-calculated outputs for all three examples here:
https://drive.google.com/drive/folders/1FI_TOFywfI-pMejpzGOuUgdwnCLe2NA5?usp=sharing

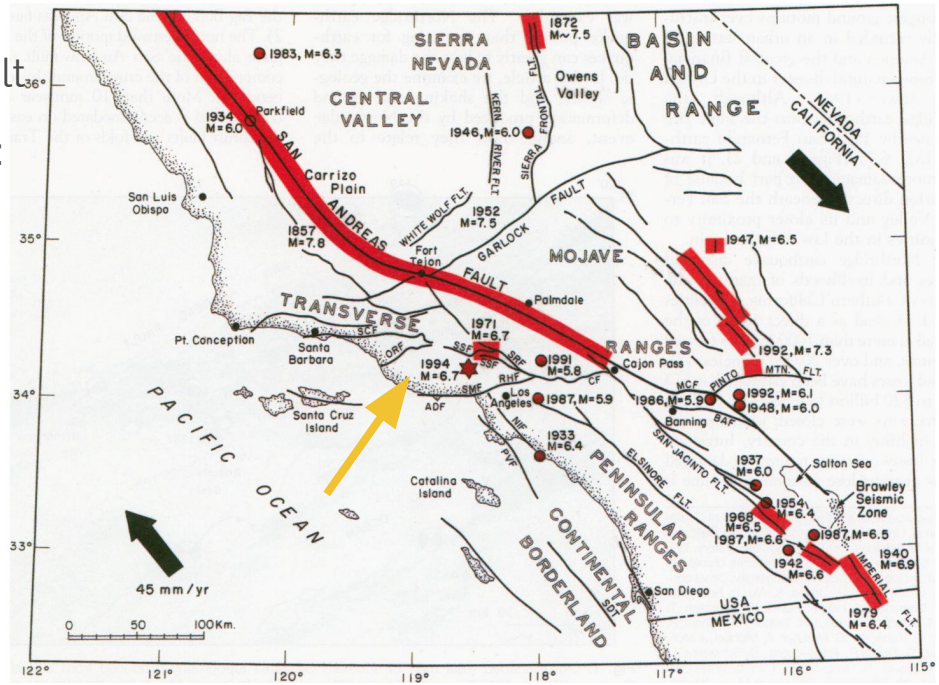
or

/shared/cheese/seissol/output/

Example 1 (kinematic): The 1994, M6.7 Northridge earthquake

- 'blind' thrusting earthquake on a unknown fault
- most costly American earthquake since 1906 : directly under the city, very strong shaking

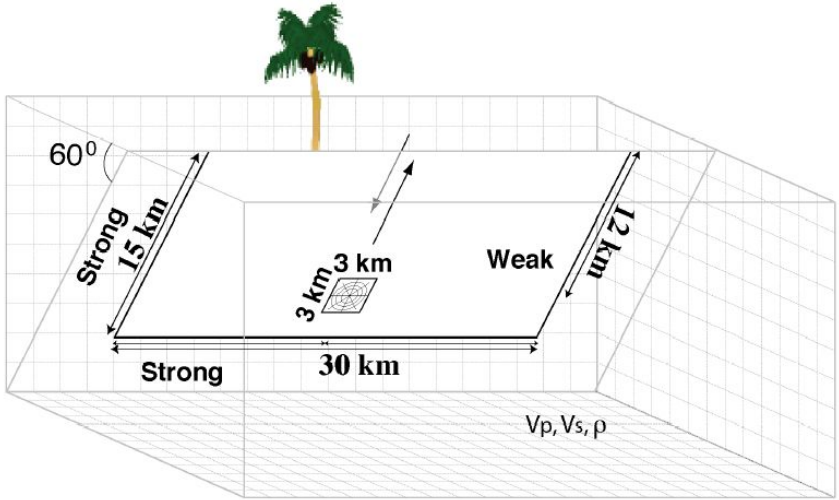


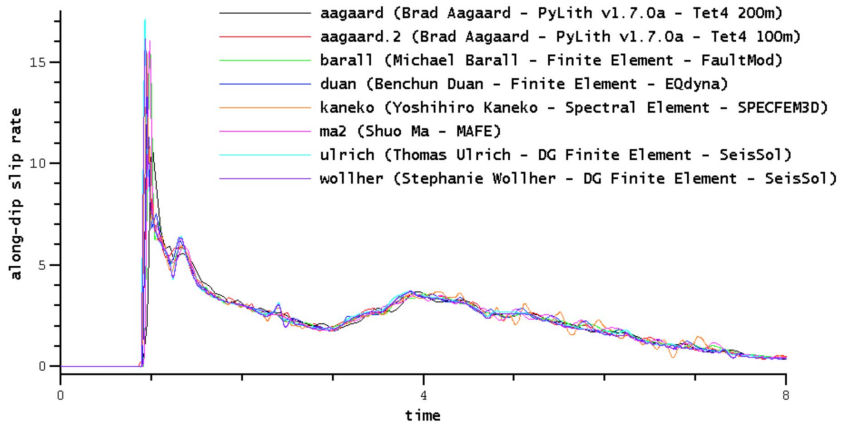


map of southern california, with major faults and historic fault ruptures (red). USGS, SCEC, science (1994)

Example 2 (dynamic): community benchmark "TPV 13"

- SCEC/USGS led effort to verify many codes for dynamic rupture (and seismic cycling) problems
- TPV13: a 3D dipping fault allowing for continuous plastic deformation off the fault





https://strike.scec.org/cvws/tpv12_13docs.html

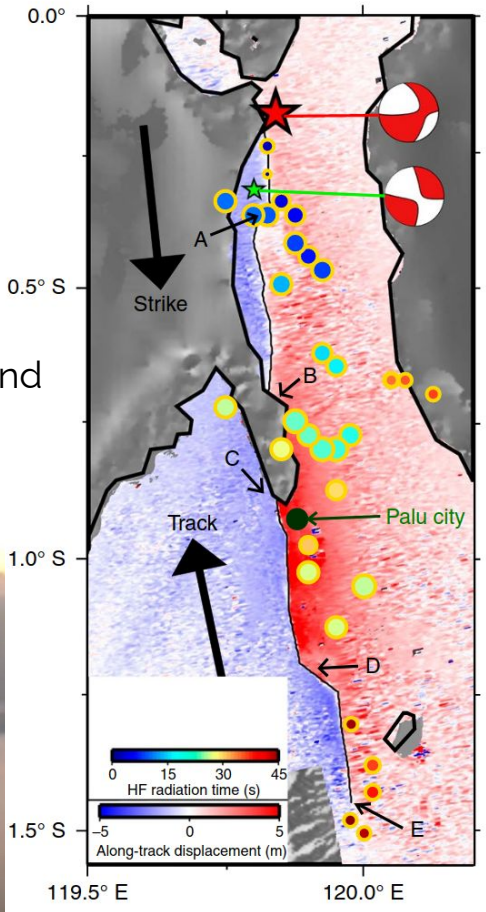
Example 3 (dynamic): 2018 Mw7.5 Palu, Sulawesi earthquake

- left-lateral, dominantly strike-slip faulting on overall straight and connected fault segments
- powerful localized tsunami
- 4,340 fatalities,

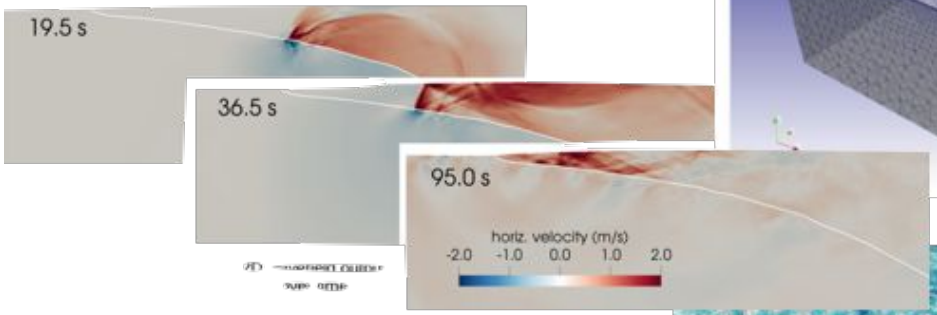
deadliest earthquake of 2018

- supershear rupture

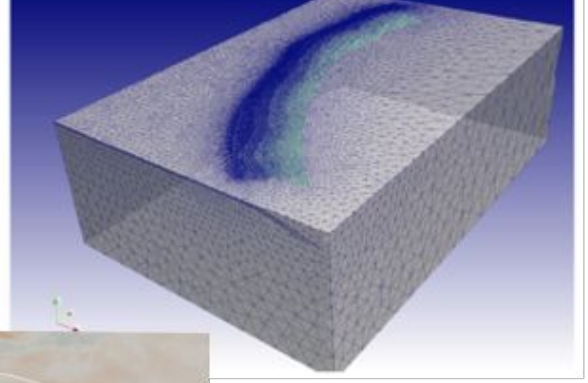
→ Back projection and INSar analysis of the Palu EQ, [Bao et al. (2019)]

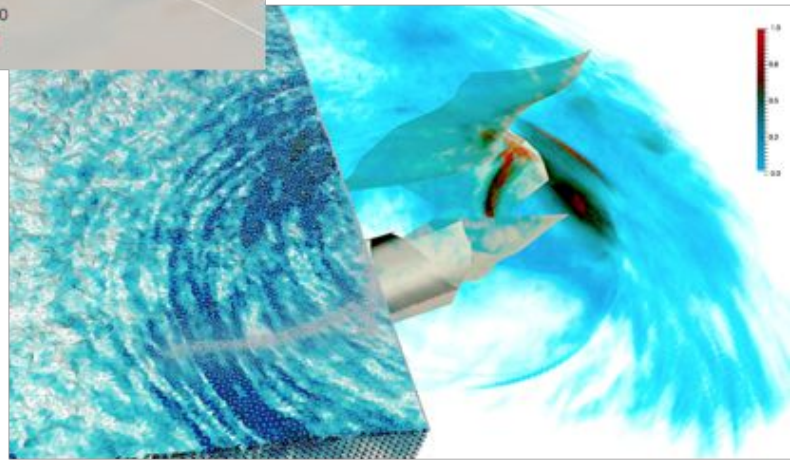


ParaView for visualizing your results



2D SeisSol (Laptop)





Kaikoura: 29 mio elements, 90 sec.,
2 hours on 3000 Sandy Bridge cores

- time series (seismograms), 2D (fault, free surface) and 3D output fields
- paraview filters for simple post-processing

Docker setup

Please open a terminal (Windows: PowerShell) and run (right now)

```
$ docker pull uphoffc/seissol-training
> docker pull uphoffc/seissol-training
```

Note: **$** Linux/Mac, **>** Windows, **$/>** all systems

Docker setup

Run in a terminal (Windows: PowerShell)

$/> docker run uphoffc/seissol-training gmsh --version

You should see “4.6.0” if everything works as it should.

Docker setup (Linux/Mac)

We need to tell Docker where it can find files on your computer. Therefore, we need a slightly more complicated command, e.g.:

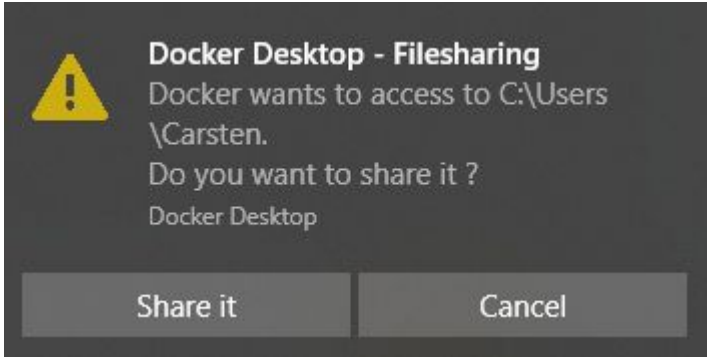
```
$ docker run -v $(pwd):/shared/ -u $(id -u):$(id -g)
uphoffc/seissol-training gmsh
```

This command mounts the current working directory (pwd) inside the container, such that the container has access to files in your current working directory.

Docker setup (Windows)

```
> docker run -v ${PWD}:/shared/ uphoffc/seissol-training gmsh
```

Click “Share it”



Docker setup

In order to simplify our lives, please download and unzip
https://github.com/SeisSol/Training/archive/main.zip

In there you find the script training.sh, which wraps the long Docker command on Linux:

```
$ ./training.sh gmsh --version
> docker run -v ${PWD}:/shared/ uphoffc/seissol-training gmsh --version
```

Terminal efficiency

Enter Ctrl + R to browse your history.

E.g., “Ctrl + R” and “docker”
finds your last docker command!

(Works in PowerShell, too.)

Example 1 - ground motions from a kinematic rupture model of the 1994 Northridge earthquake

seismic wave propagation from many point sources, specifically moment tensor sources, describing a kinematic finite earthquake model

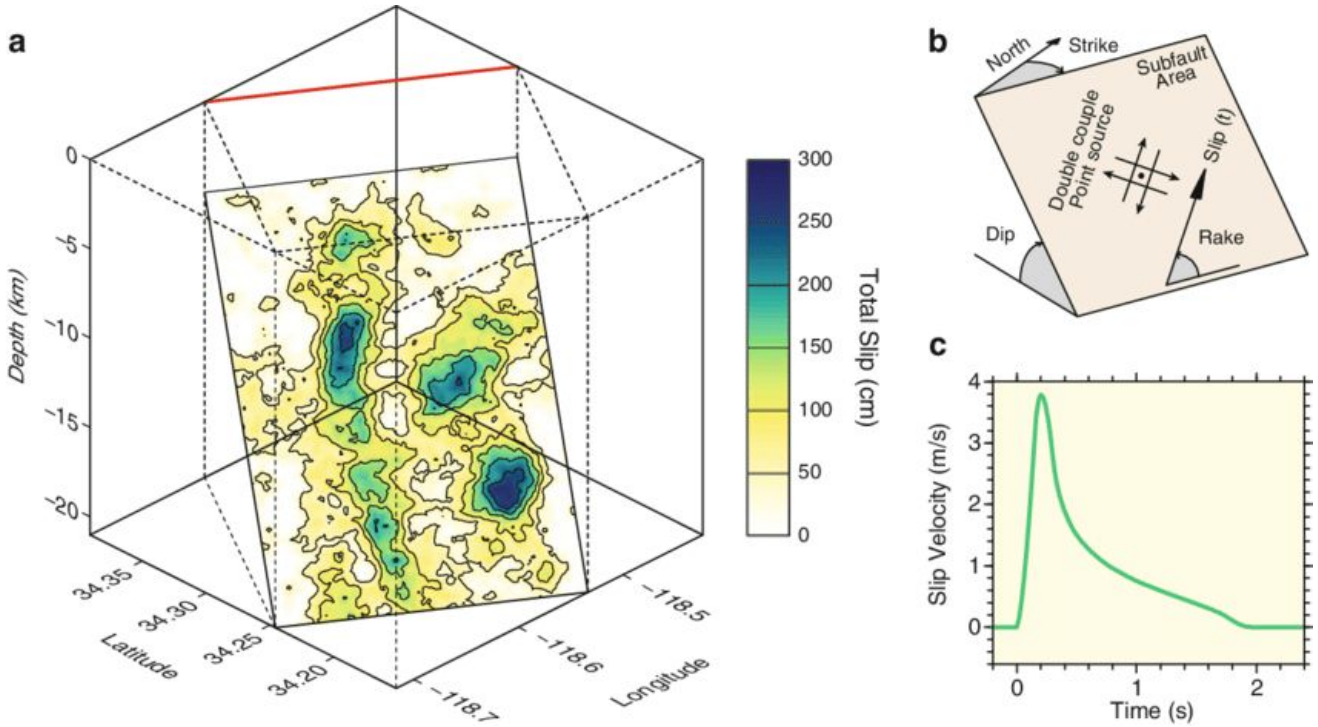
Kinematic source representation

Fig. from Taborda and Roten, 2015

earthquake kinematics

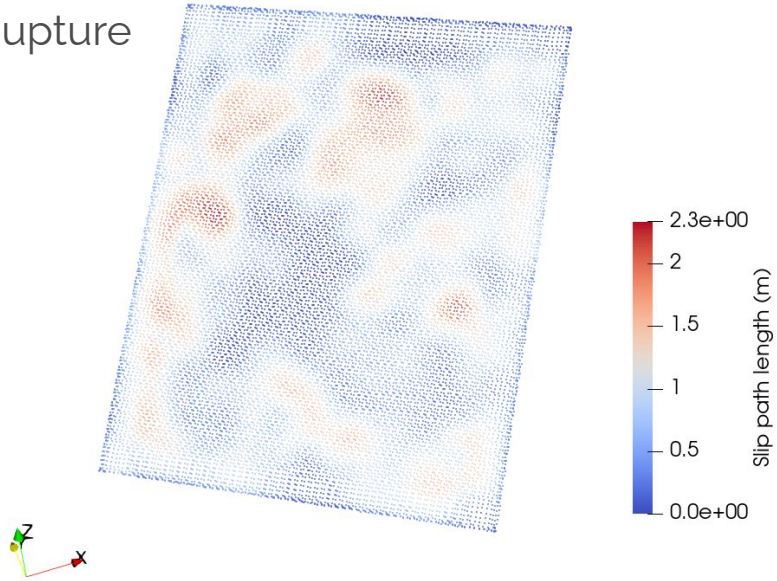
described as a set of point sources, each described with a moment tensor and source time function,

often derived from solving an inverse problem (e.g., using seismic, geodetic data)



Model description

- kinematic rupture model from Hartzell et al., 1996 in a 3D subsurface model using the SCEC Standard Rupture Format (SRF)
  https://strike.scec.org/scecpedia/Standard_Rupture_Format
- geometry: 20 x 25 km planar fault, 40° dipping
- smoothed/resampled temporally and spatially



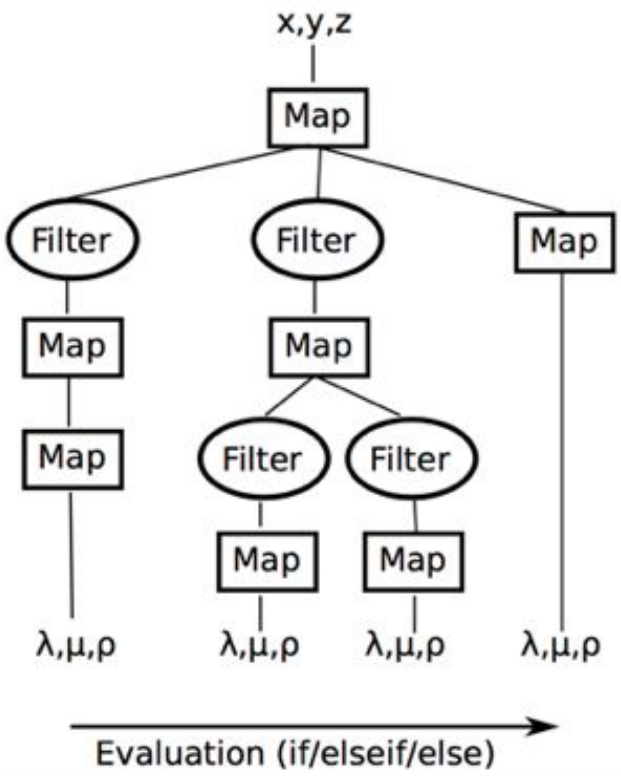
Parameter setup

- Parameter file: **parameters.par**
  - **defines input/output paths, spatial and temporal discretisation, global simulation parameters, etc.**
- Several dependent files (easi): **yaml**
  - **specify spatial variation of input parameters**

    (also supports temporal variability in principle)

easi composition principle

- easy initialization of parameters
- written in the YAML markup language
- different types of maps and filters
- highly flexible, no hardcoded setup-dependent code, favours reproducibility
- https://github.com/SeisSol/easi



easi: illustration

```
!Any
components:
  - !GroupFilter
    groups: [6,7,8]
    components: !ConstantMap
      map:
        rho:     2500.0
        mu:         0.0
        lambda: 1.96e10
  - !FunctionMap
    map:
      rho:    return 1600. + 59.5*pow(y,1./3.);
      mu:     return 0.;
      lambda: return pow(260. + 30*sqrt(y), 2.) * (1600. + 59.5*pow(y,1./3.));
```

Constant properties in volume regions 6, 7 and 8 (regions are defined within the mesh)

Else, spatial variations with y

parameters.par

https://seissol.readthedocs.io/en/latest/parameter-file.html

```
&equations
! yaml file defining spatial dependance of material properties
MaterialFileName = 'northridge_material.yaml'
/
&IniCondition
/
&Boundaries
BC_fs = 1    ! enable free surface boundaries
BC_dr = 0    ! enable fault boundaries
BC_of = 1    ! enable absorbing boundaries
/
&SourceType
Type = 42   ! 42: finite source type in netcdf format
FileName = 'northridge_resampled.nrf'   ! name of input file
/
```

parameters.par

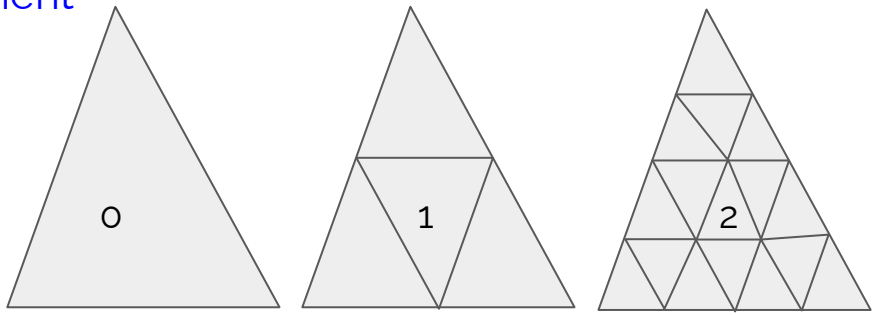
https://seissol.readthedocs.io/en/latest/parameter-file.html

```
&SpongeLayer
/
&MeshNml
MeshFile = 'mesh_northridge.puml.h5' ! hdf5 unstructured tetrahedral mesh
meshgenerator = 'PUML'               ! name of mesh generator
/
&Discretization
CFL = 0.5            ! The Courant-Friedrichs-Levy (CFL) Stability Criterion (<=1.0)
ClusteredLTS = 2
! 1 for global time-stepping, 2,3,5,...for local time-stepping
! Elements are clustered by their time-step in the time bins
! [t_{min} * ClusteredLTS^c, t_{min} * ClusteredLTS^{c+1})
! where t_{min} = min_{element} t_{element} and c in N_0 is chosen such that
! t_{min} * ClusteredLTS^c <= t_{element}
! Default choice: ClusteredLTS = 2
```

parameters.par

https://seissol.readthedocs.io/en/latest/parameter-file.html

```
&Output
FaultOutputFlag = 0                    ! write 2D dynamic rupture output across fault interfaces
OutputFile = 'output/northridge'       ! output files will be written to a folder named 'output' and
                                       all output files will have 'northridge' prefix
Format = 10                            ! Volume output format (10= no output, 6=hdf5 output)
!                  |stress    |vel  |plastic strain output (if any)
iOutputMask = 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
TimeInterval =  5.0      ! output time interval of volume output every 5 seconds
refinement = 1           ! use sub-element refinement

! free surface output parameters
SurfaceOutput = 1     ! activate surface output
SurfaceOutputRefinement = 1
SurfaceOutputInterval = 1.0
printIntervalCriterion = 2
! how output frequency is chosen, based on: 1=#timesteps, 2=time (s), 3=timesteps+time
```



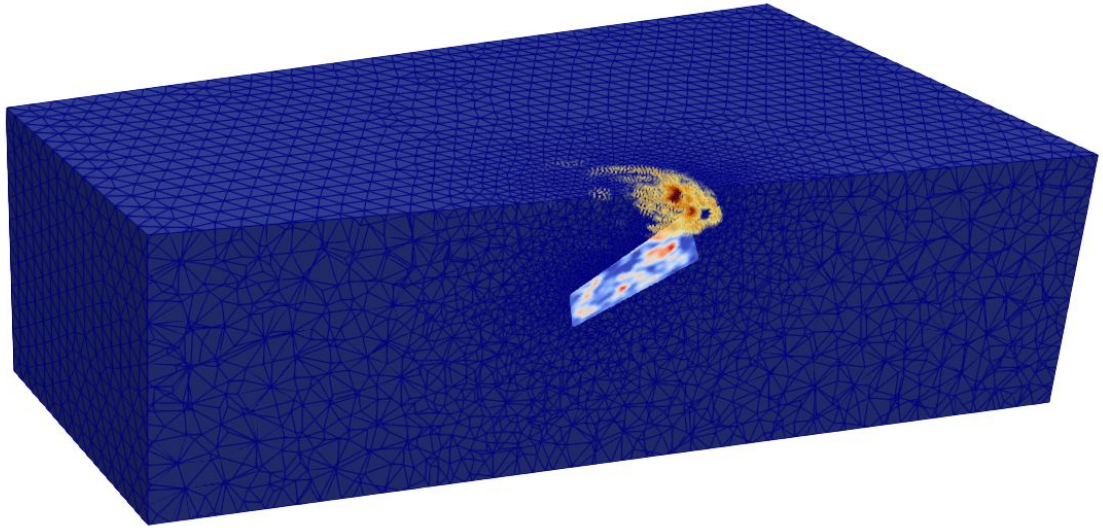
parameters.par

https://seissol.readthedocs.io/en/latest/parameter-file.html

```
pickdt = 0.005                    ! synthetic seismogram sampling of 0.005 s
pickDtType = 1                    ! Pickpoint Type (1 = time, 2 = timestep(s))
nRecordPoints = 6                 ! number of receivers
RFileName = 'offreceivers.dat'    ! receiver coordinates (ASCII file, x y z)

!xdmfWriterBackend = 'posix' ! (optional)
! The backend used in fault, wavefield, and free-surface output.
! The 'hdf5' backend is only supported when SeisSol is compiled with HDF5 support.
/
&AbortCriteria
EndTime = 10.0 ! the simulation will run for 10 seconds physical time
/
&Analysis
/
&Debugging
/
```

offreceivers.dat

x1 y1 z1
x2 y2 z2
x3 y3 z3
...



Locations of nRecordPoints seismometers recording during the simulation in (x,y,z) in meters
positive z is up

Standard rupture format

ASCII file format to store moment tensor sources (restricted to double-couple).

specification file:

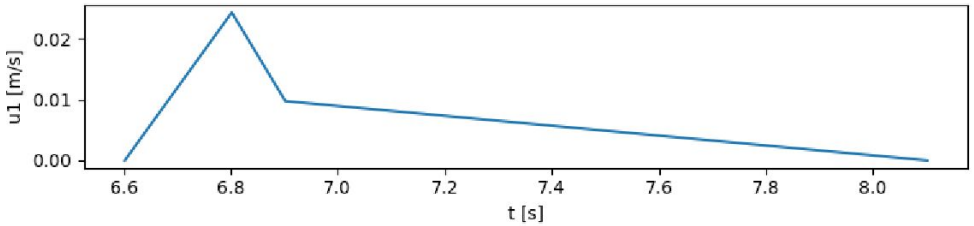
http://hypocenter.usc.edu/research/SRF/srf-v2.0_rev1.pdf

‘Standard’ rupture format

LON	LAT	DEP	STK	DIP	AREA	TINIT	DT	(	VS	DEN)
RAKE	SLIP1	NT1	SLIP2	NT2	SLIP3	NT3				
SR1[1]	SR1[2]	SR1[3]	. . .	SR1[NT1]						
SR2[1]	SR2[2]	SR2[3]	. . .	SR2[NT3]						
SR3[1]	SR3[2]	SR3[3]	. . .	SR3[NT3]						

version 2.0 only

LON	longitude of subfault center
LAT	latitude of subfault center
DEP	depth of subfault center (km)
STK	strike
DIP	dip



Hand's on! (45 minutes)

We will go into breakout rooms to do the exercise in small groups. Later we will meet again in the main zoom room.

The trainers will help you during the exercise, you will use your own machine and the cluster.

1. coordinate system

2 problems: Standard Rupture Format (SRF) uses a geographic coordinate system. ASCII files are not efficient for a large number of point sources or a highly sampled source time function.

1 solution: convert to Netcdf Rupture Format (NRF) with **rconv**.

laptop/desktop:
transform the coordinate system of the kinematic source model efficiently

```
$ ./training.sh rconv -i northridge_resampled.srf -o northridge_resampled.nrf -x visualization.xdmf -m "+proj=merc +lon_0=-118 +y_0=-4050981.42 +x_0=57329.54 +units=m +axis=enu"
```

The “-m” option specifies the projection with which the computational mesh was created.

“+axis=enu” means x=east, y=north, u=up. Convention must match your computational mesh.

Hint: Find suitable projections for your region of interest on https://epsg.io/.

2. login to training cluster & access SeisSol training material

```
$ scp northridge_resampled.nrf sca50XXX@training.hlrs.de:work/
$ ssh sca50XXX@training.hlrs.de
$ cd work
$ cp -r /shared/cheese/seissol/setups/* .
$ mv northridge_resampled.nrf Northridge/
```

training cluster:
What is a job script?

```
#!/bin/bash
#PBS -N seissol
# name of the job
#PBS -l select=1:node_type=sb:ncpus=16:mpiprocs=1:mem=16gb,walltime=02:00:00
# 1 node (sandbridge architecture), 16 CPU, 1 rank, 16Gb of Ram, 2h walltime# ....
cd $PBS_O_WORKDIR
# directory from which the job was submitted (same as where the input files are)
module load compiler/intel
module load mpi/impi
# Run SeisSol with MPI
mpirun -n 1 /shared/cheese/seissol/SeisSol_Release_dsnb_4_elastic
parameters.par
```

training cluster:
run SeisSol

$ **cd Northridge**

(before submit job, please check if DGPATH, parameter files, mesh file, etc, exists in current folder !)

$ **qsub submit.sh**

To check job status:

$ **qstat**

desktop/laptop: post-processing

- copy output files from remote (HLRS) to local (desktop/laptop)
- in your terminal:

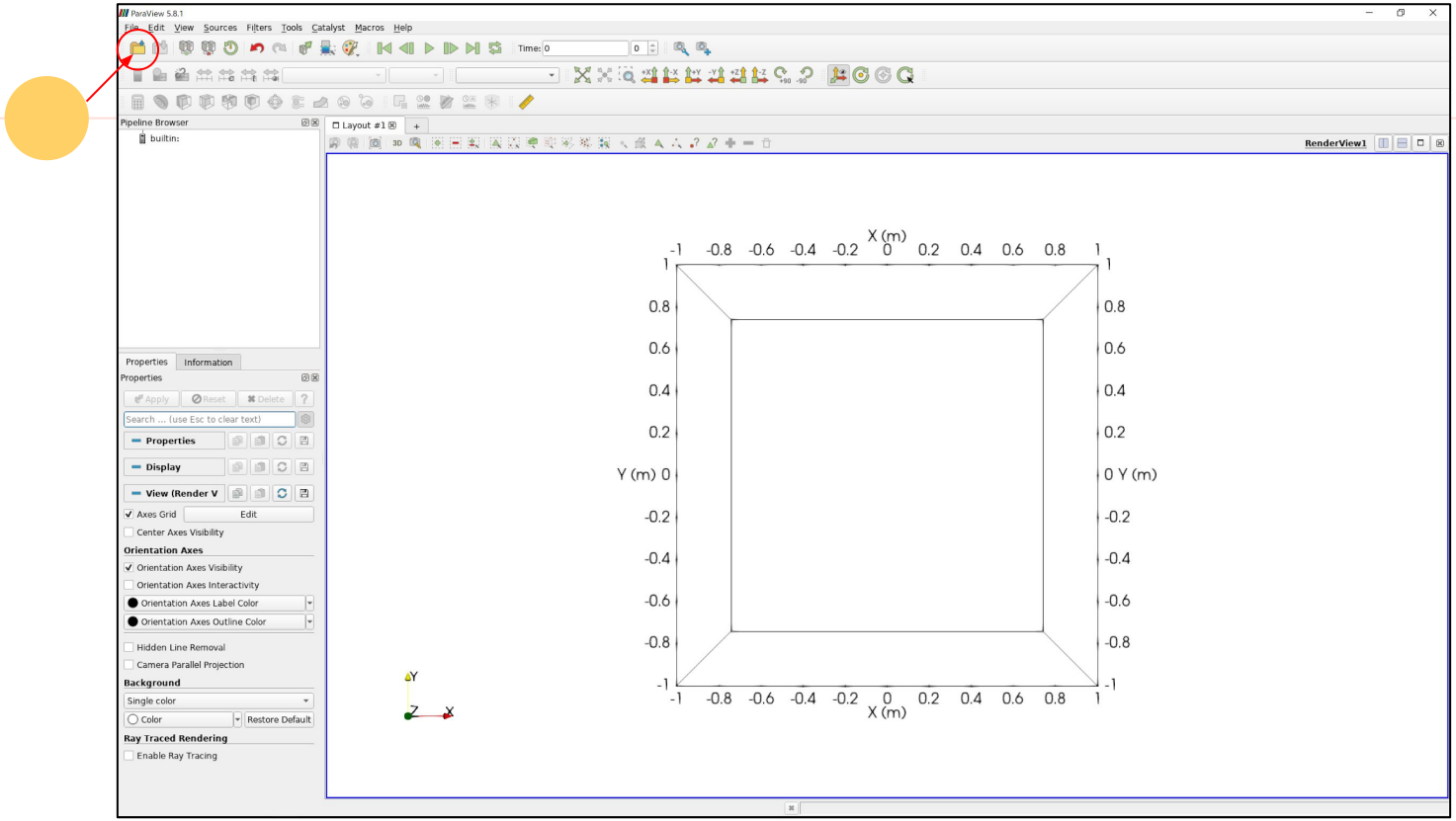
```
$ scp -r scaXXXXX@training.hlrs.de :work/Northridge/output .
```

- we will use Paraview to visualize the output, apply simple filters, and generate a simple shake map (PGV)
- longer output (10 seconds) can be downloaded from `/shared/cheese/seissol/output/Northridge/`

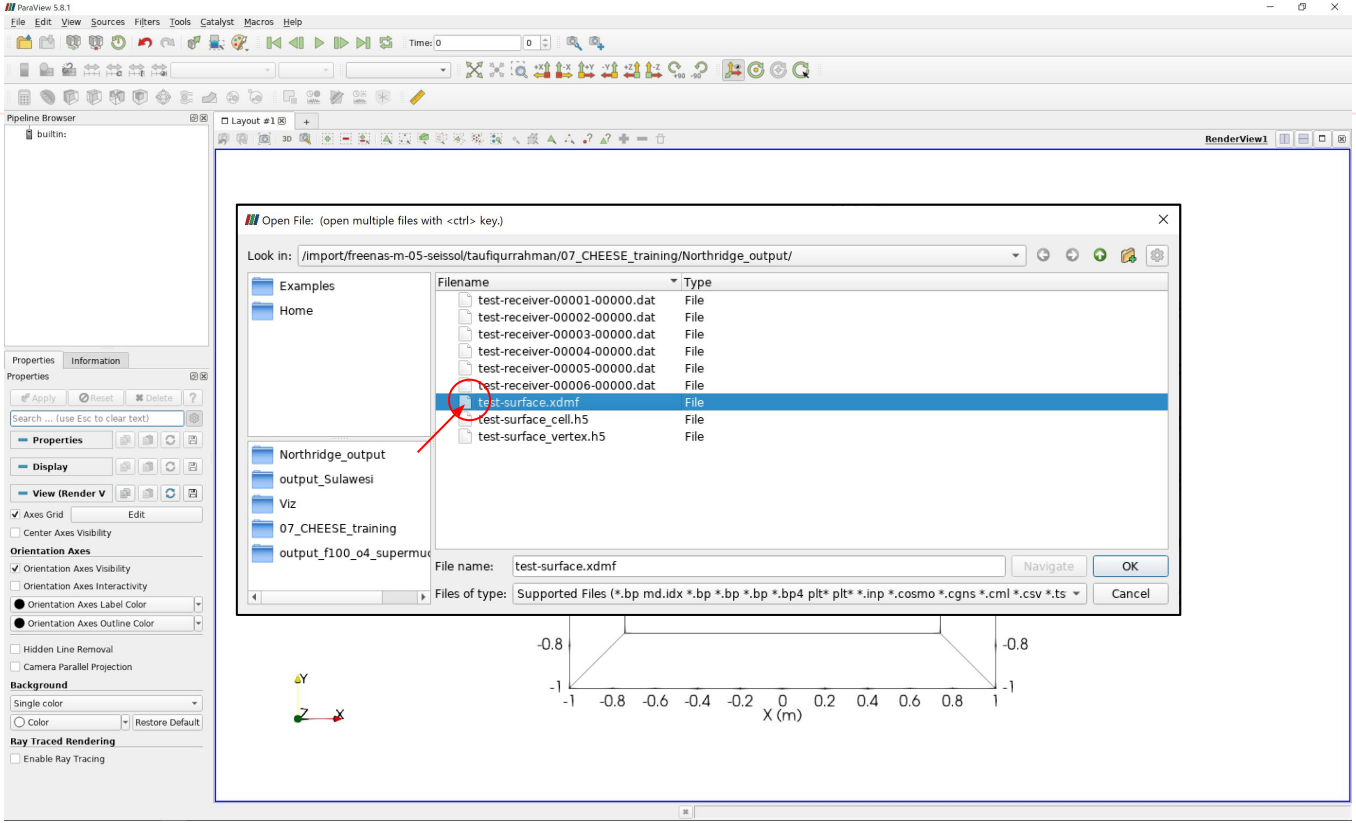
Done (for now)!

Let's get back to the main zoom room

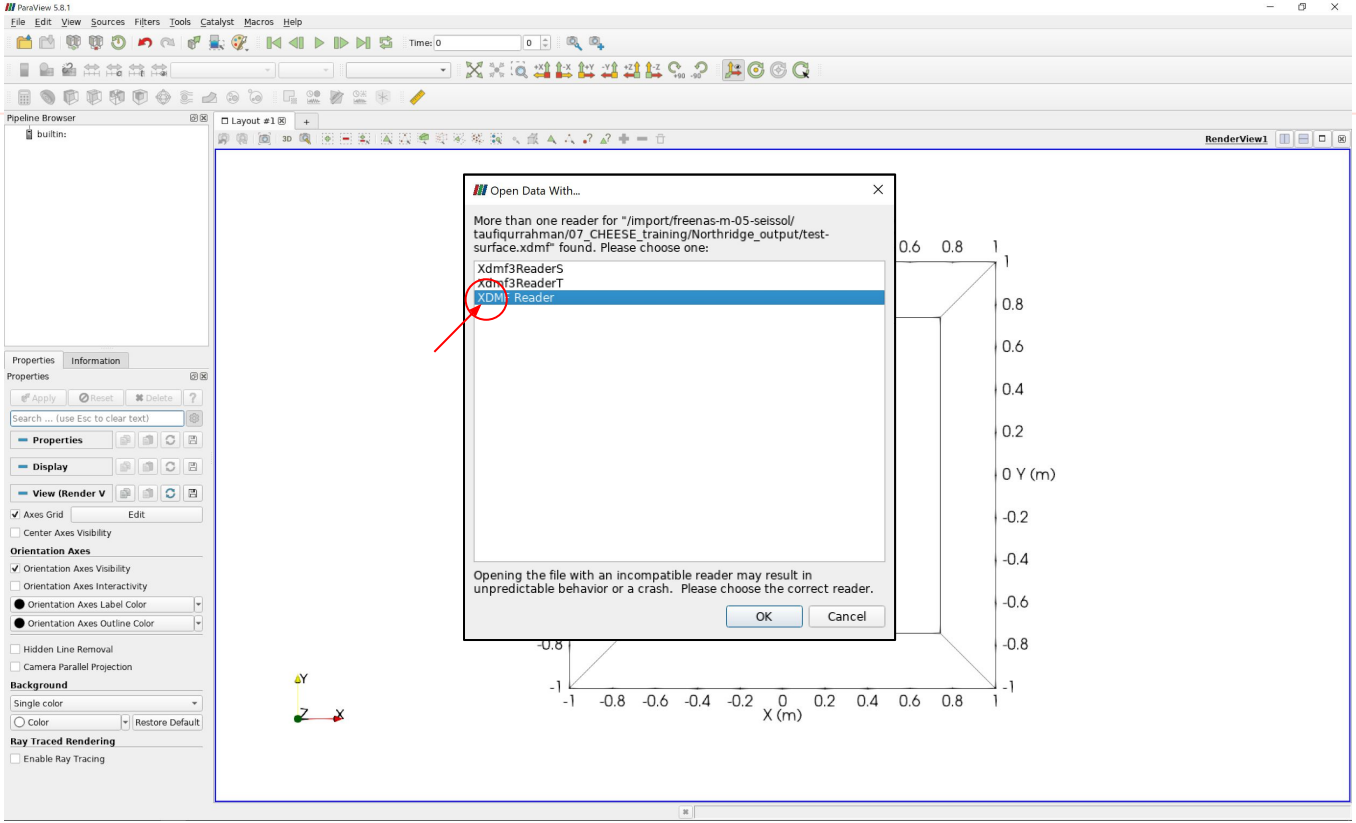
local desktop/laptop, ParaView: open file



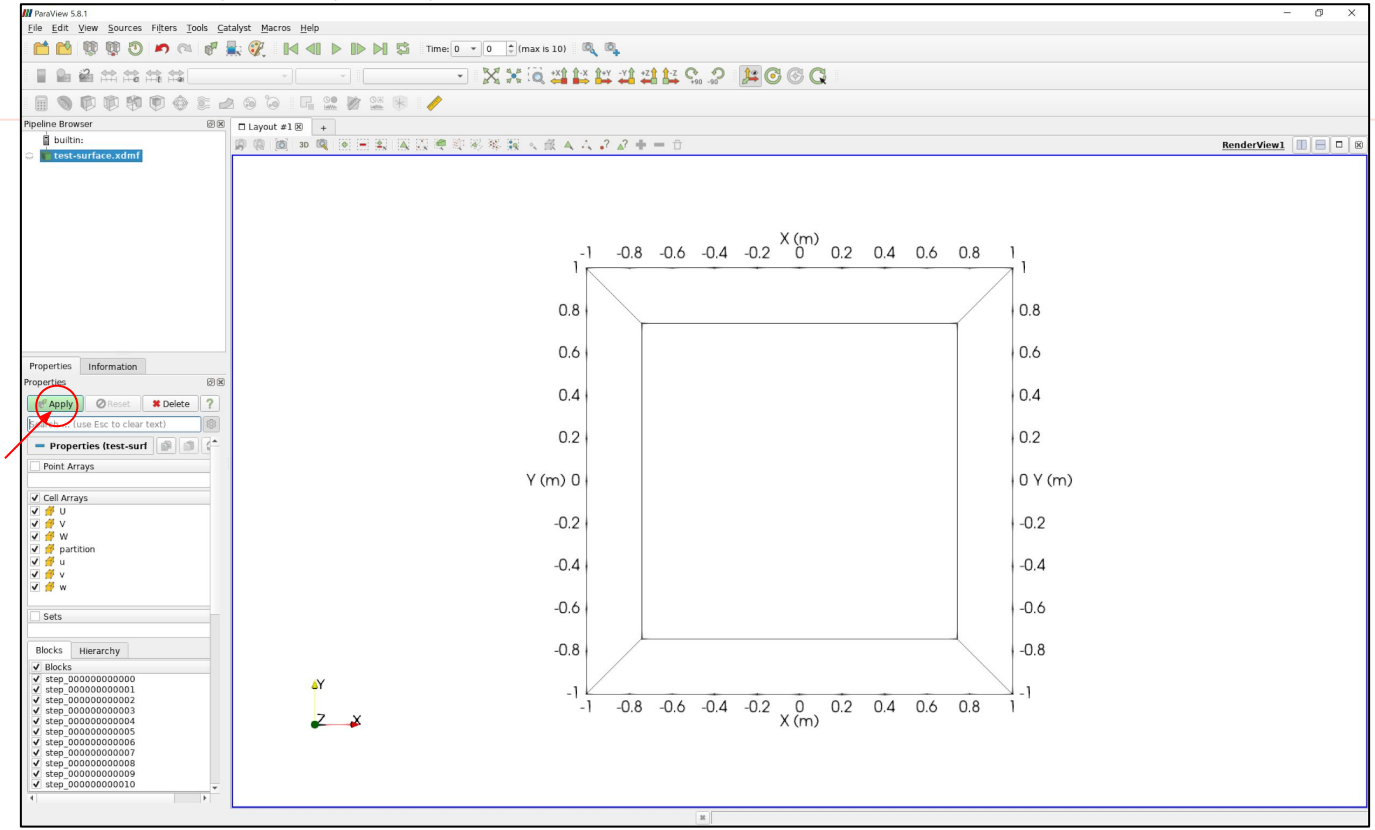
local desktop/laptop, ParaView: load free surface 2D output



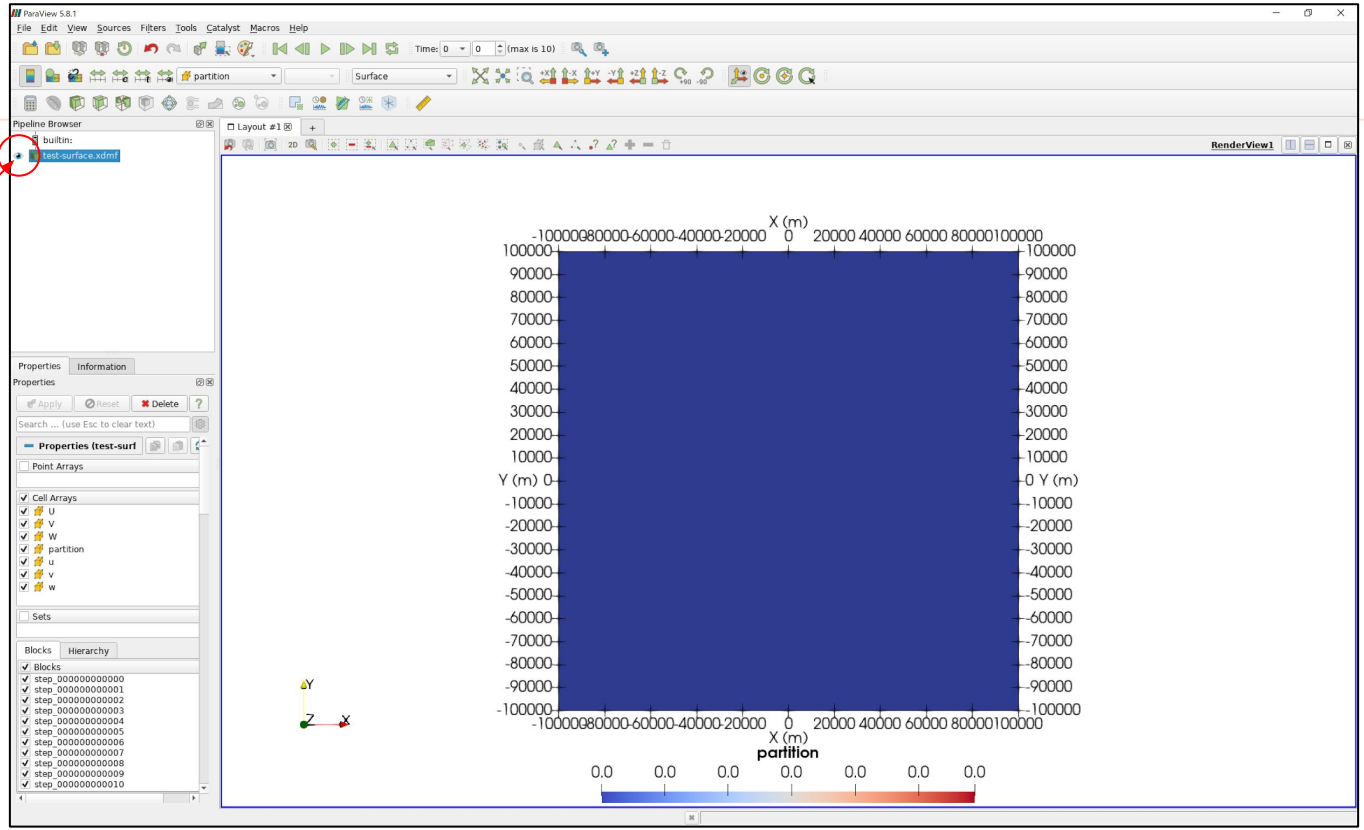
local desktop/laptop, ParaView: load free surface 2D output



local desktop/laptop, ParaView: load free surface 2D output

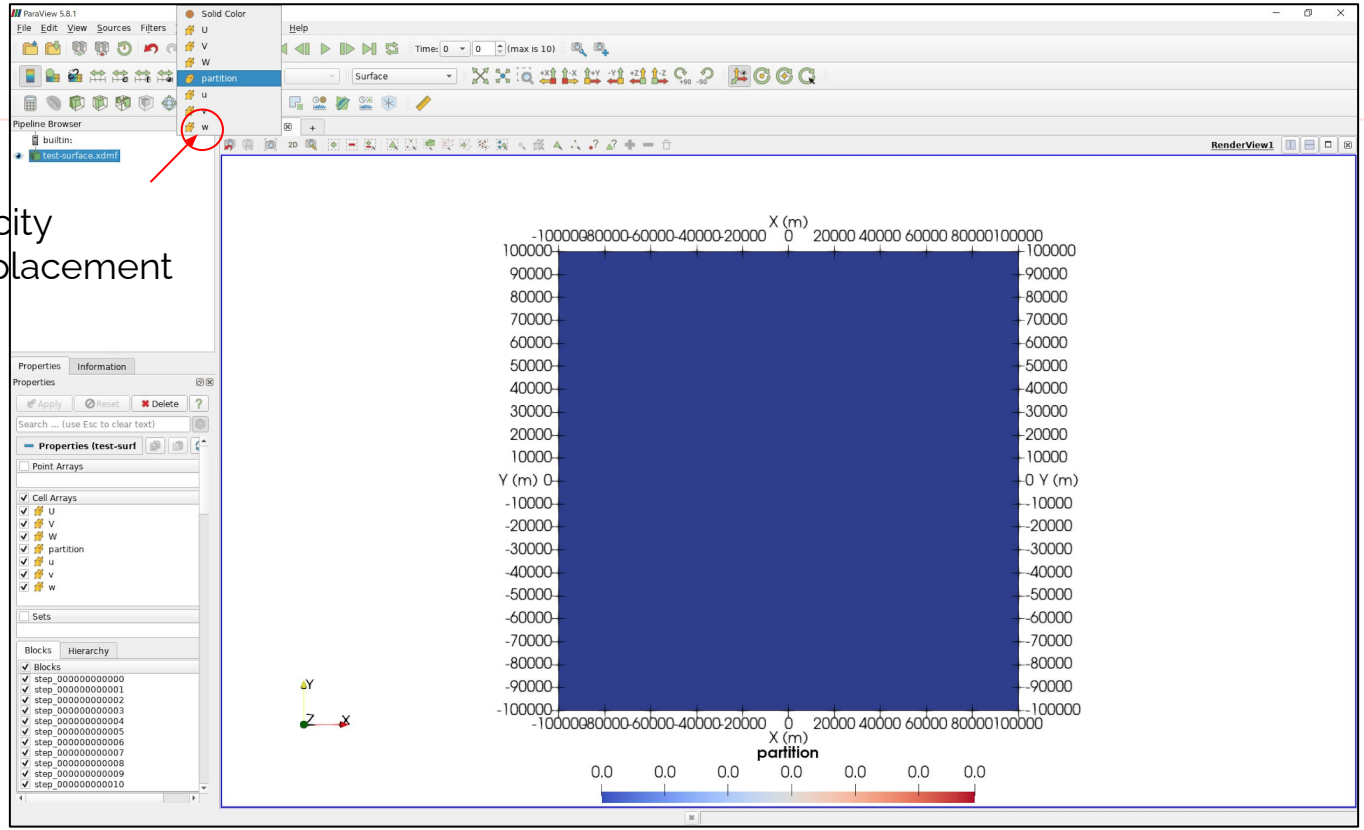


local desktop/laptop, ParaView: analyse free surface output

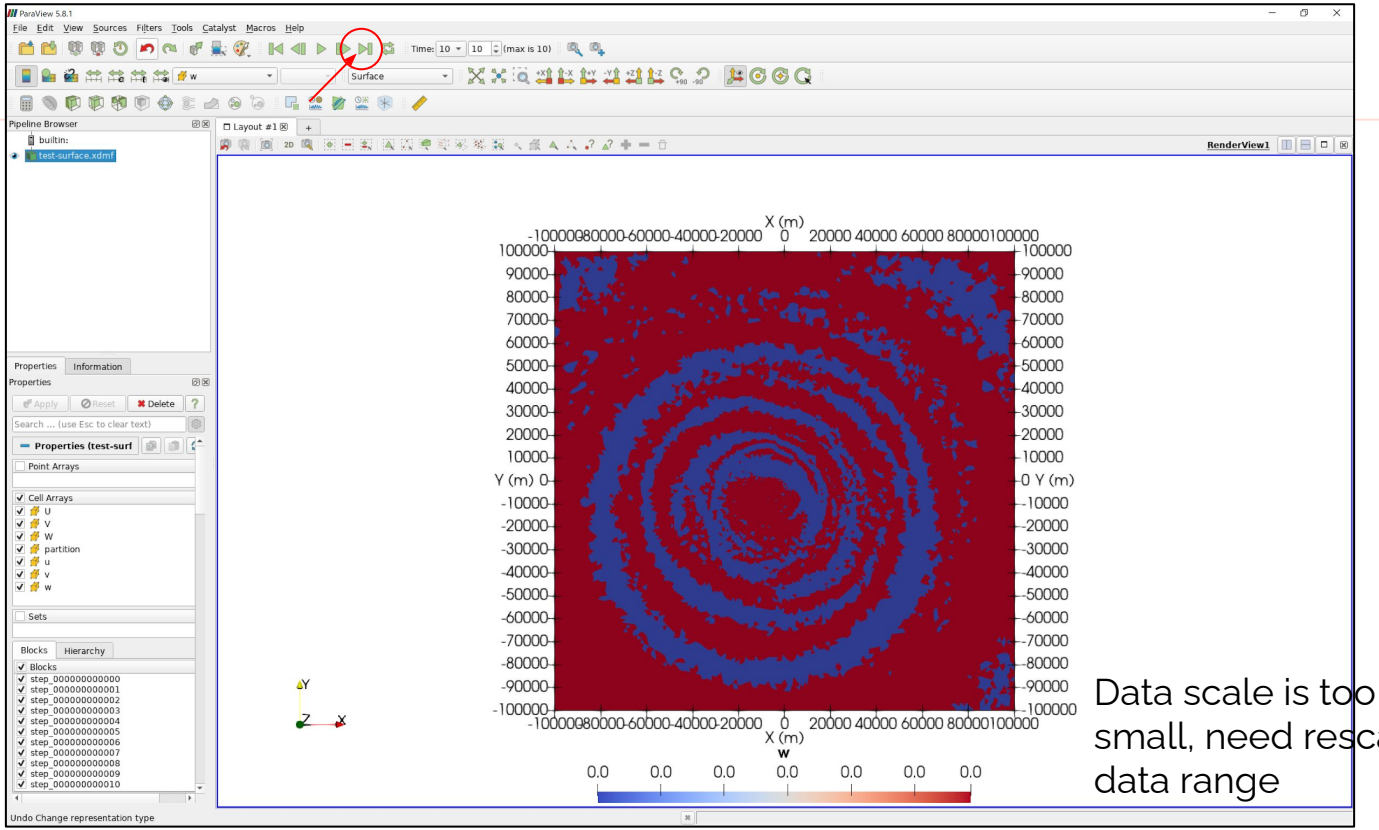


local desktop/laptop, ParaView: select an output attribute

u, v, w : velocity
U, V, W : displacement

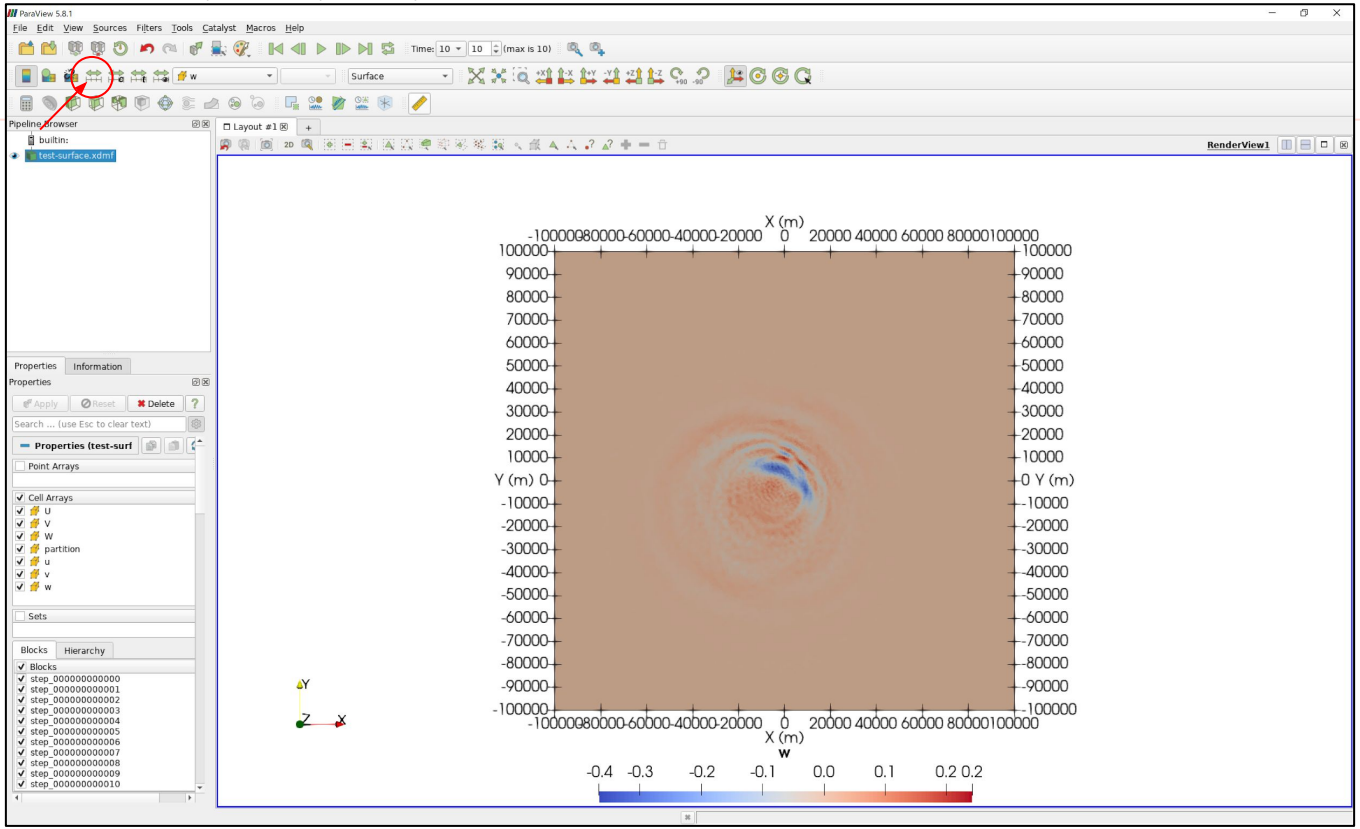


local desktop/laptop, ParaView: move to the last time step

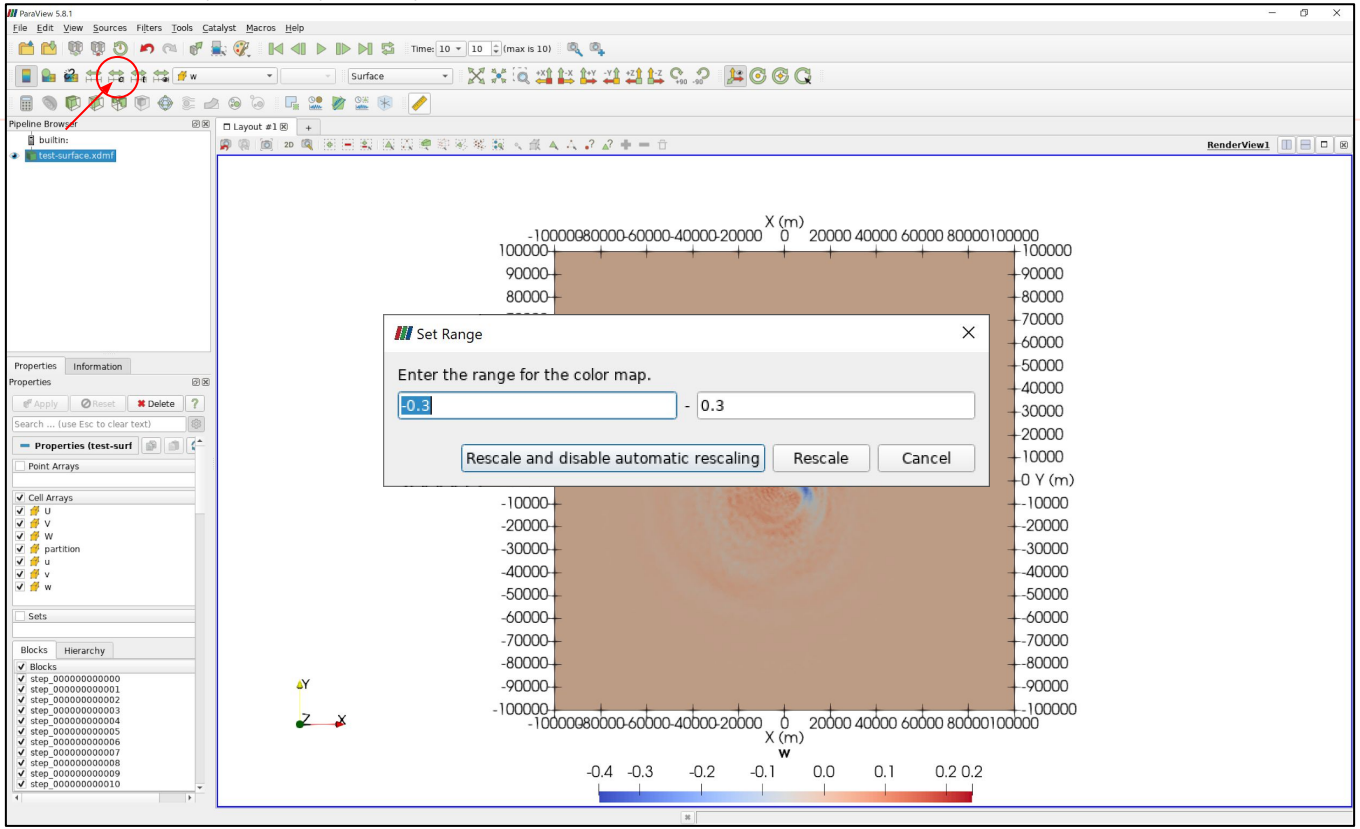


Data scale is too small, need rescale to data range

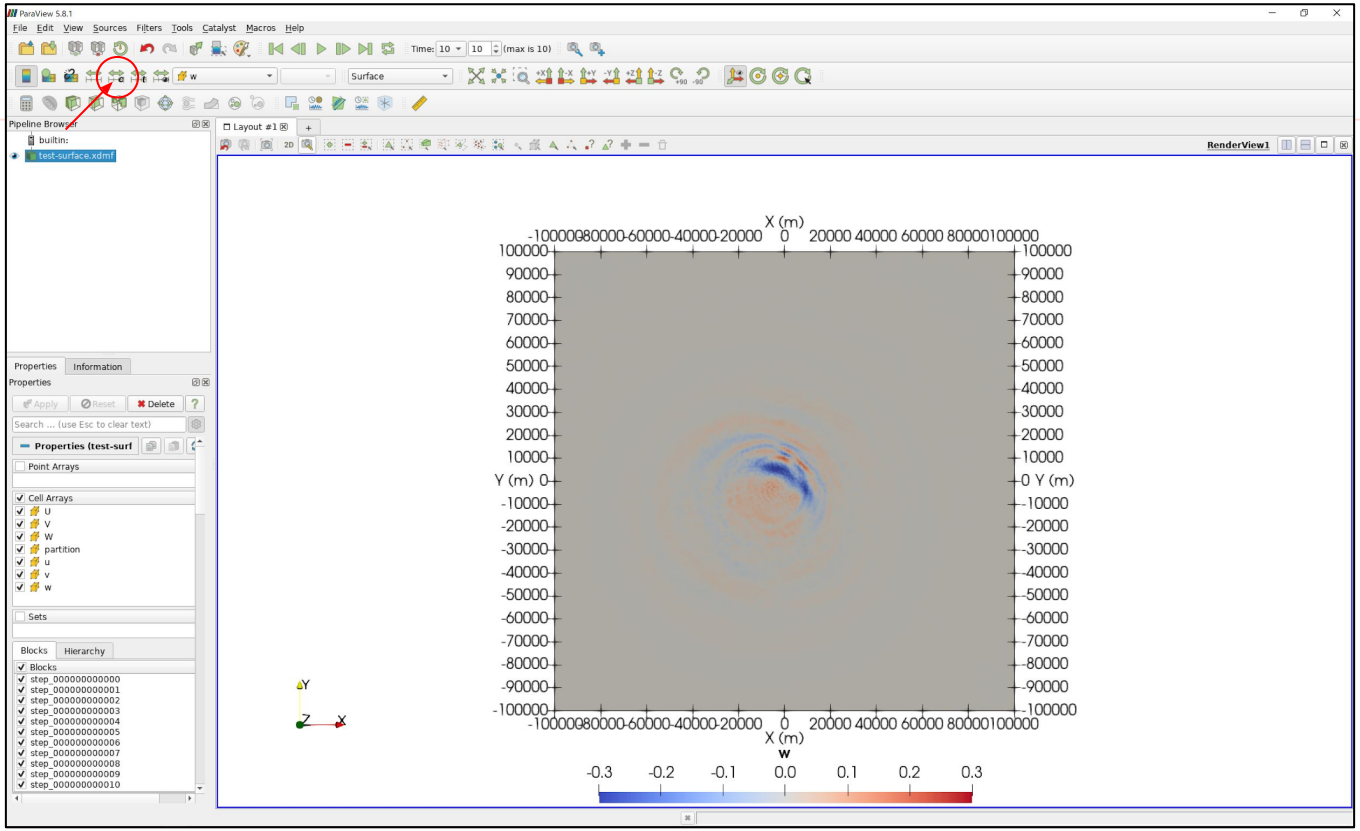
local desktop/laptop, ParaView: rescale to data range



local desktop/laptop, ParaView: rescale to custom data range

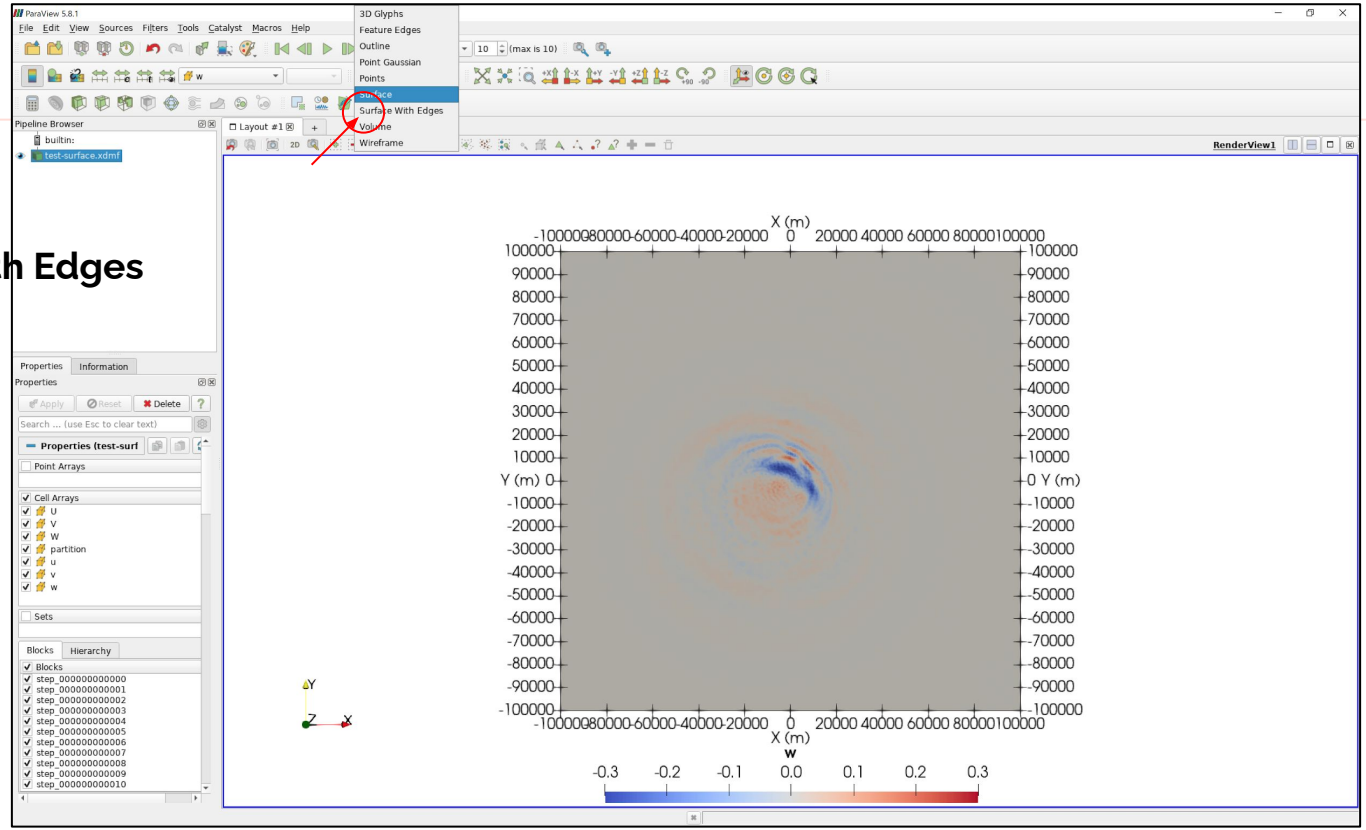


local desktop/laptop, ParaView: rescale to custom data range

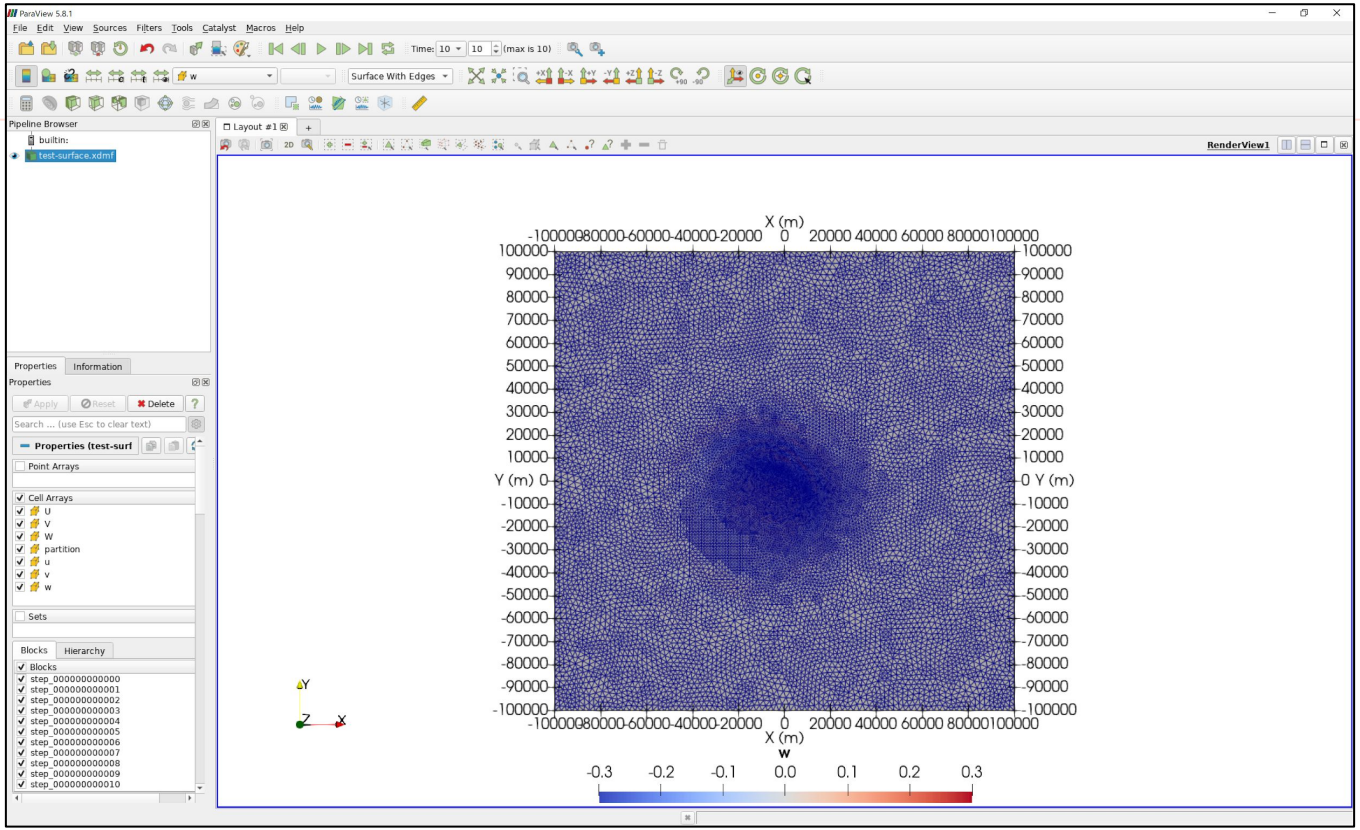


local desktop/laptop, ParaView: show element edges

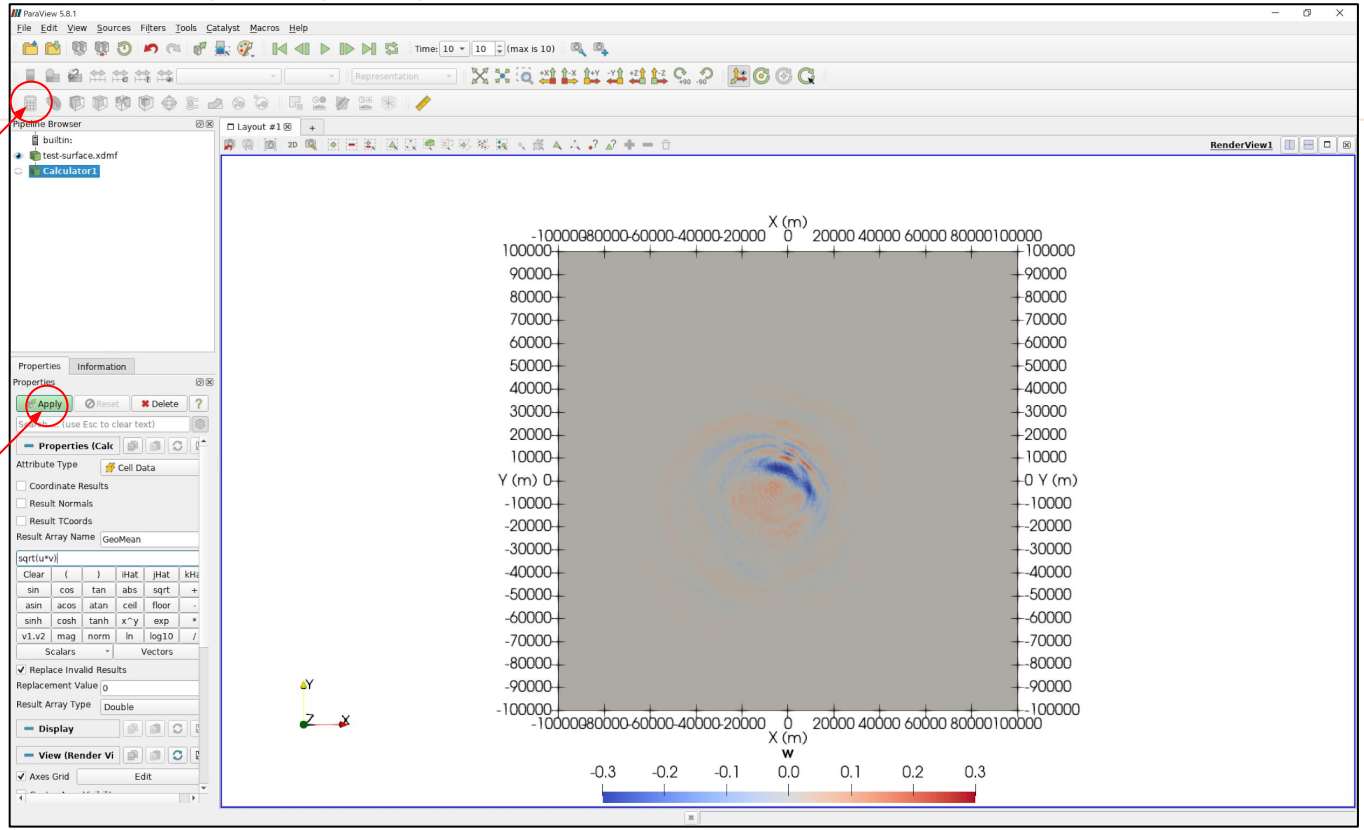
select
Surface With Edges



local desktop/laptop, ParaView: show element edges

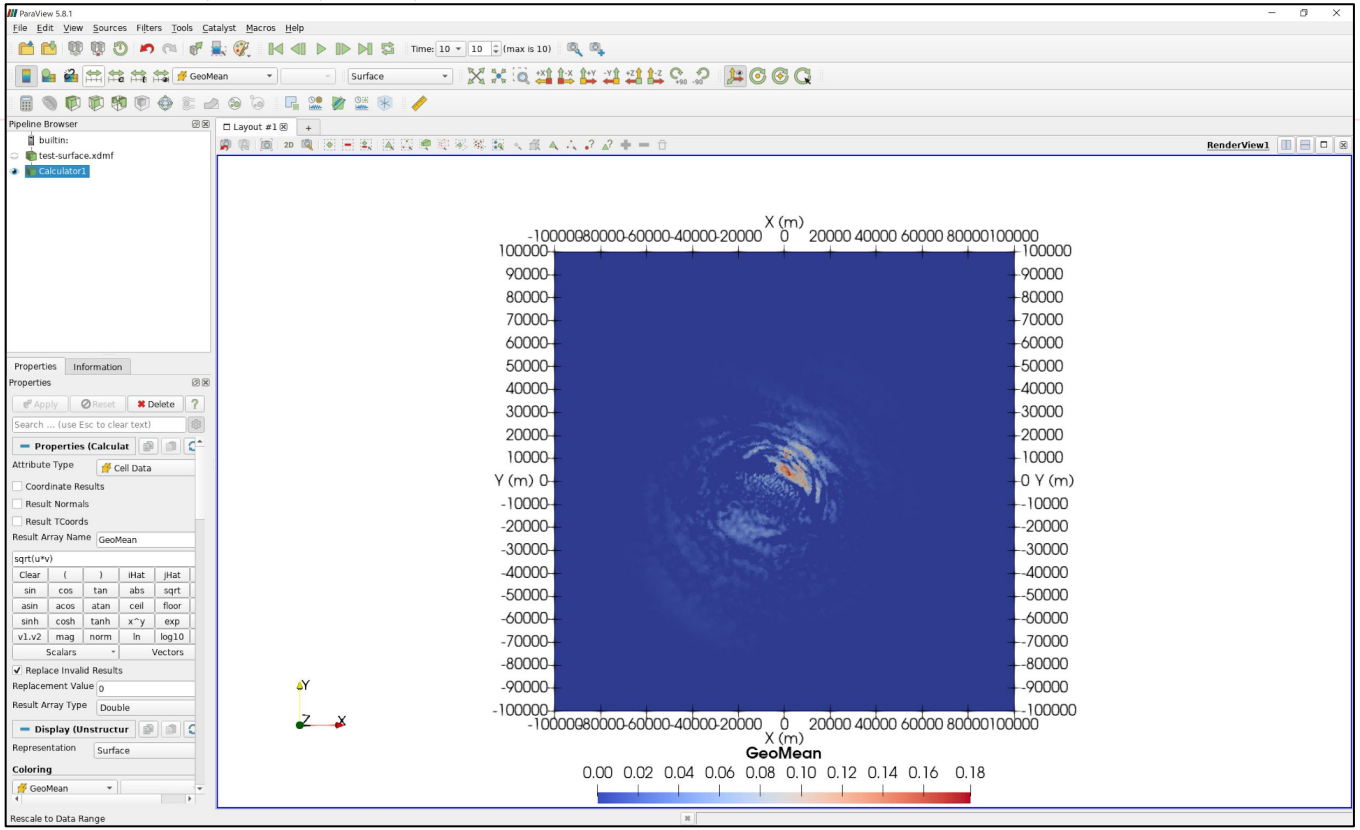


local desktop/laptop, ParaView: calculator

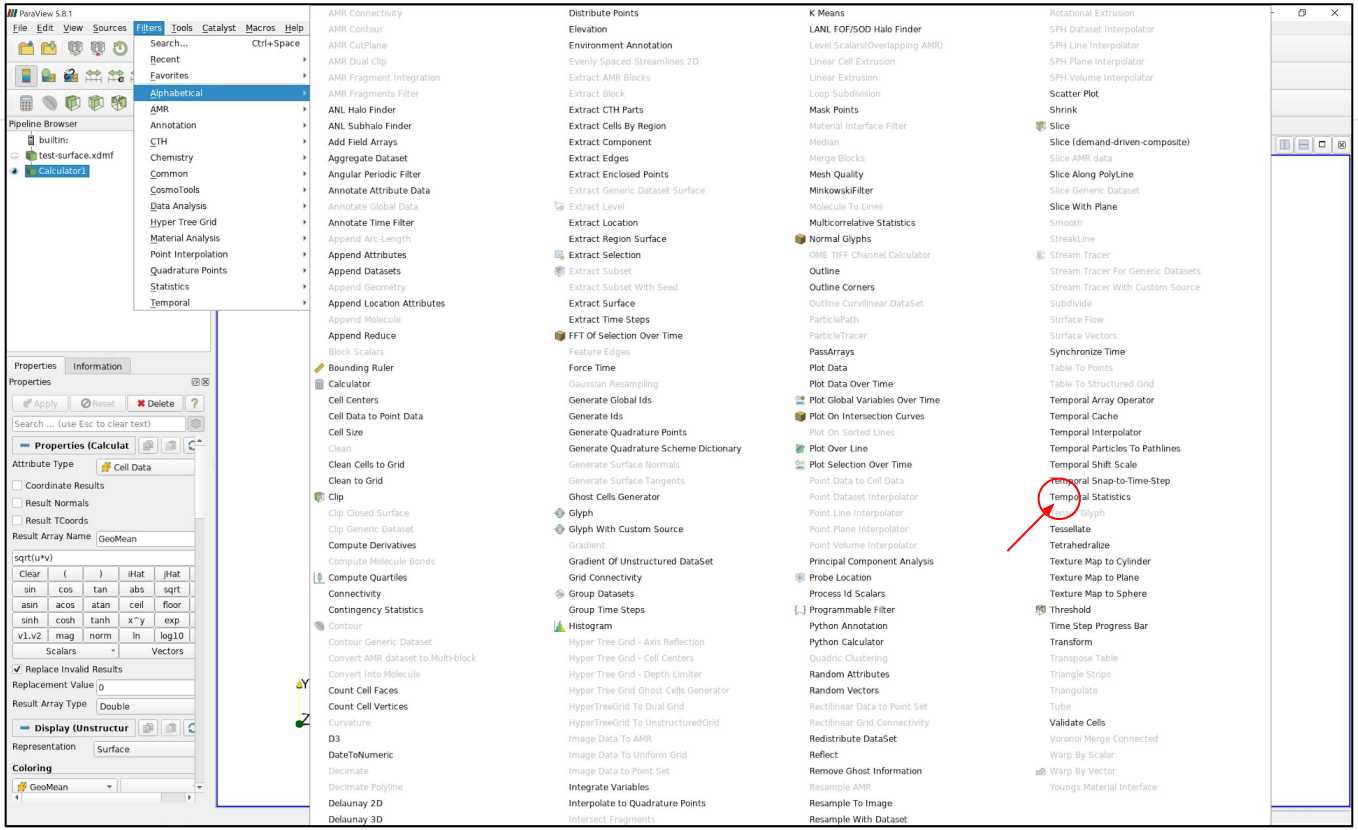


compute velocity geometrical mean

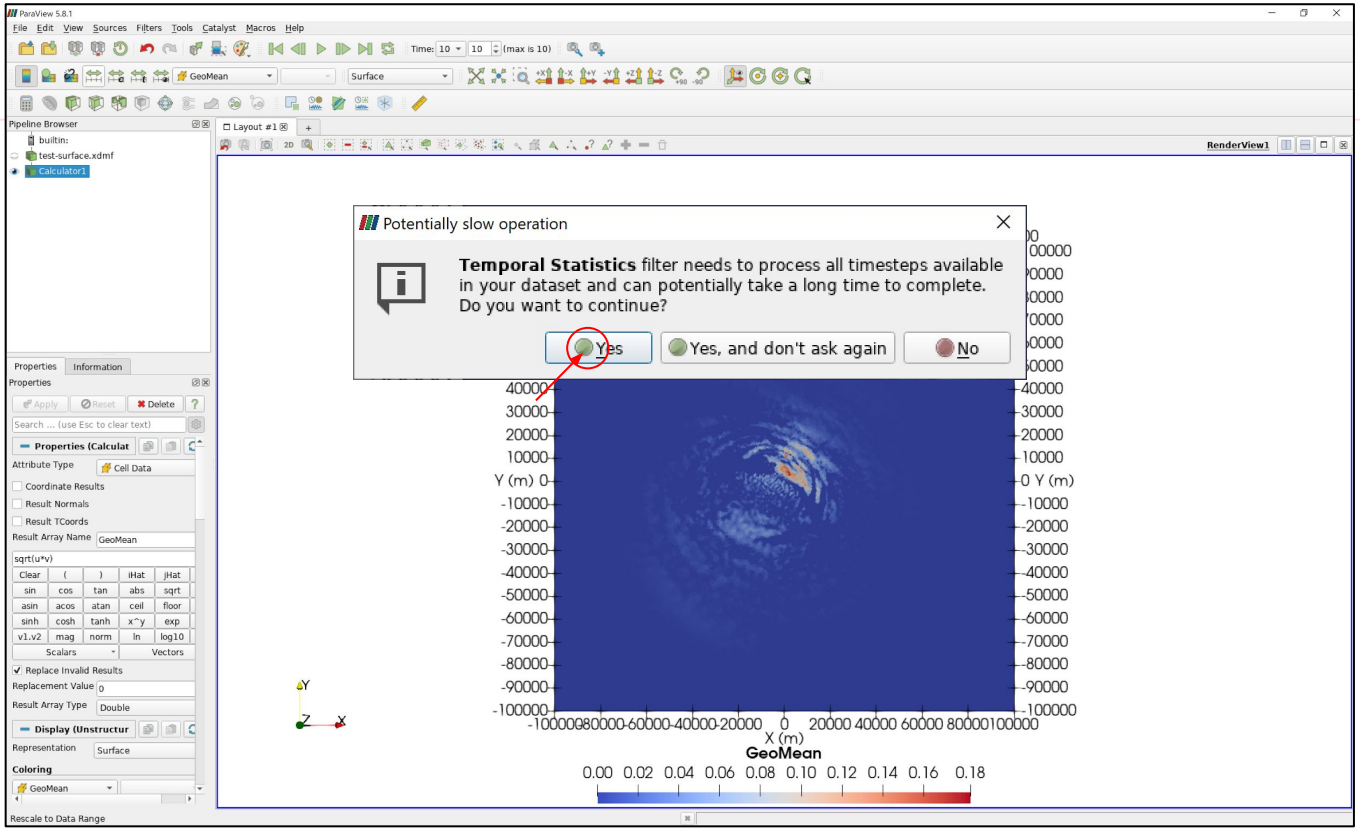
local desktop/laptop, ParaView: calculator



local desktop/laptop, ParaView: TemporalStatistics filter

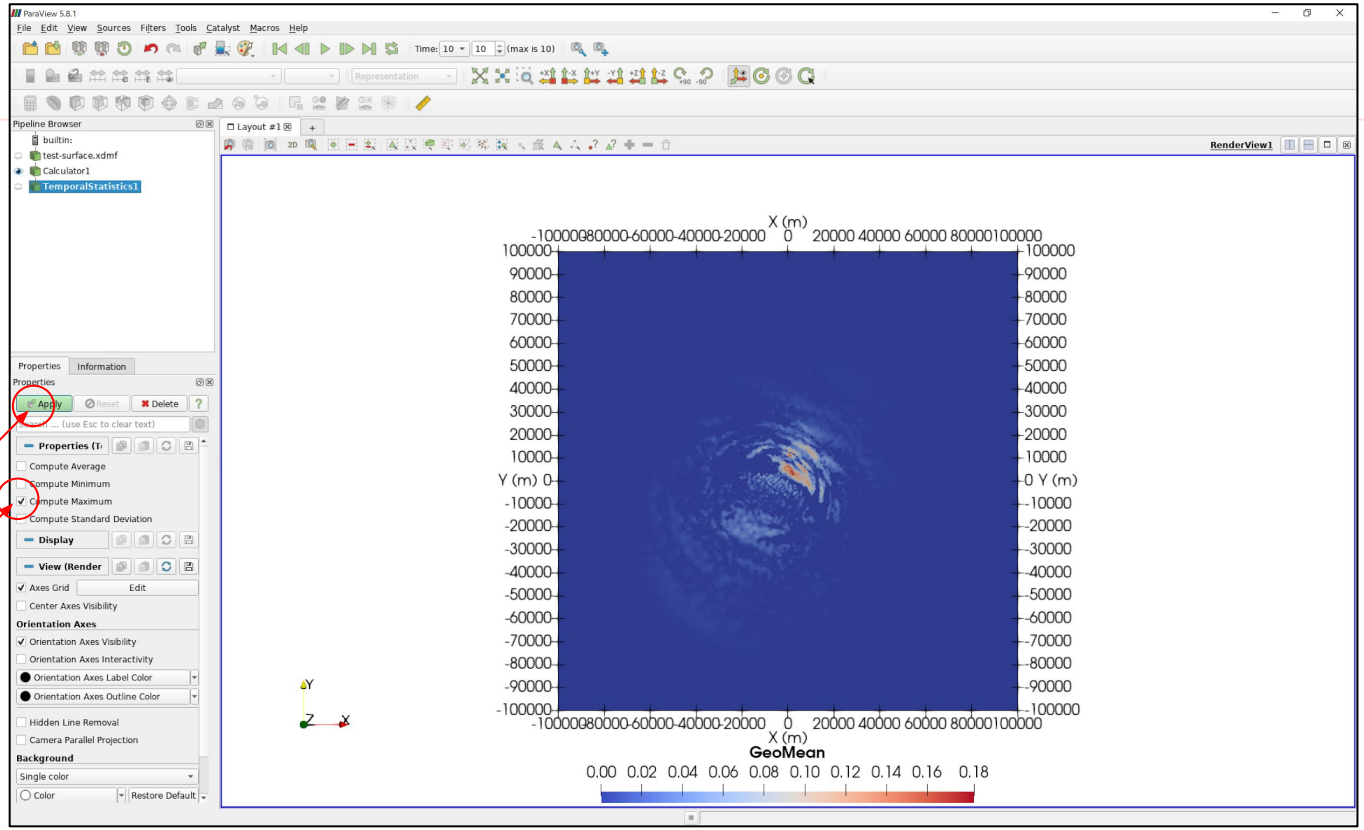


local desktop/laptop, ParaView: TemporalStatistics filter

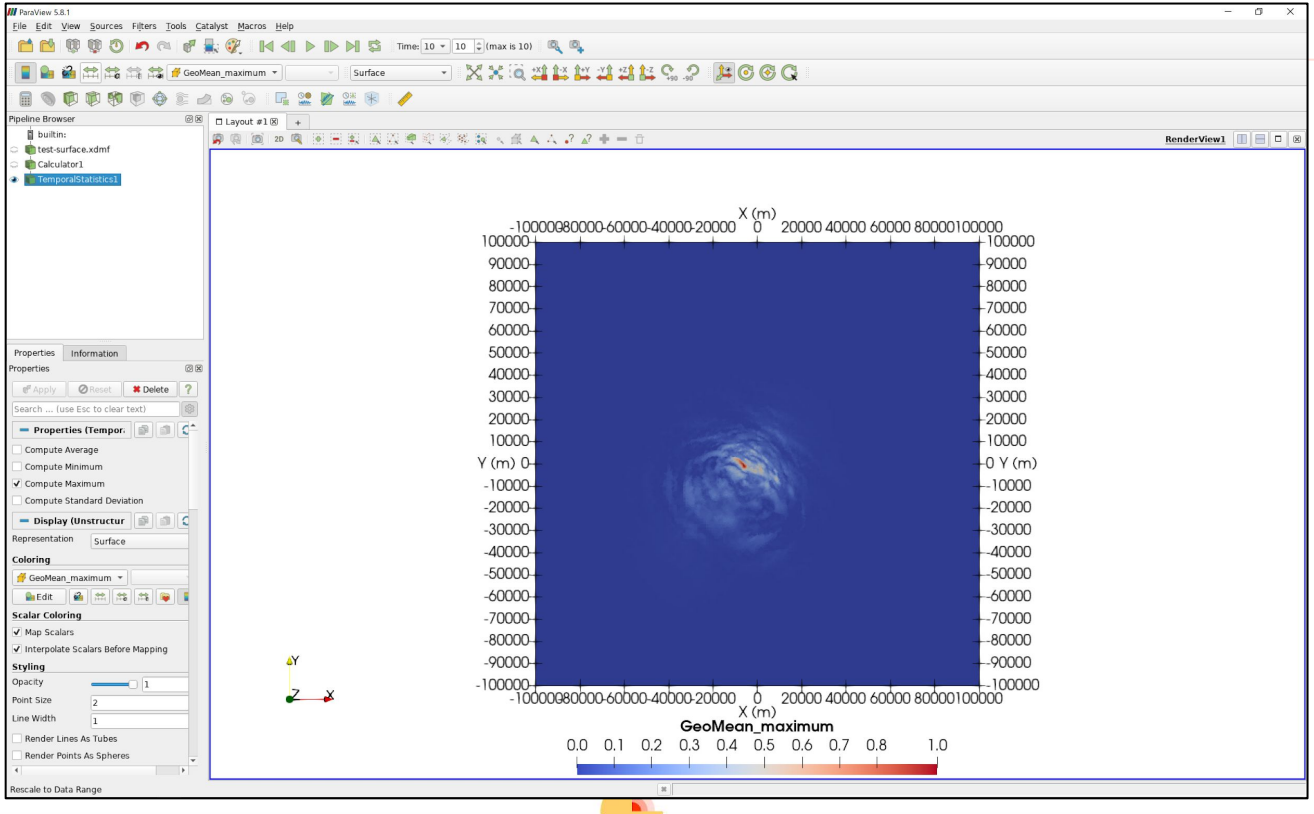


local desktop/laptop, ParaView: TemporalStatistics filter

Compute Maximum value of all timesteps then **Apply**



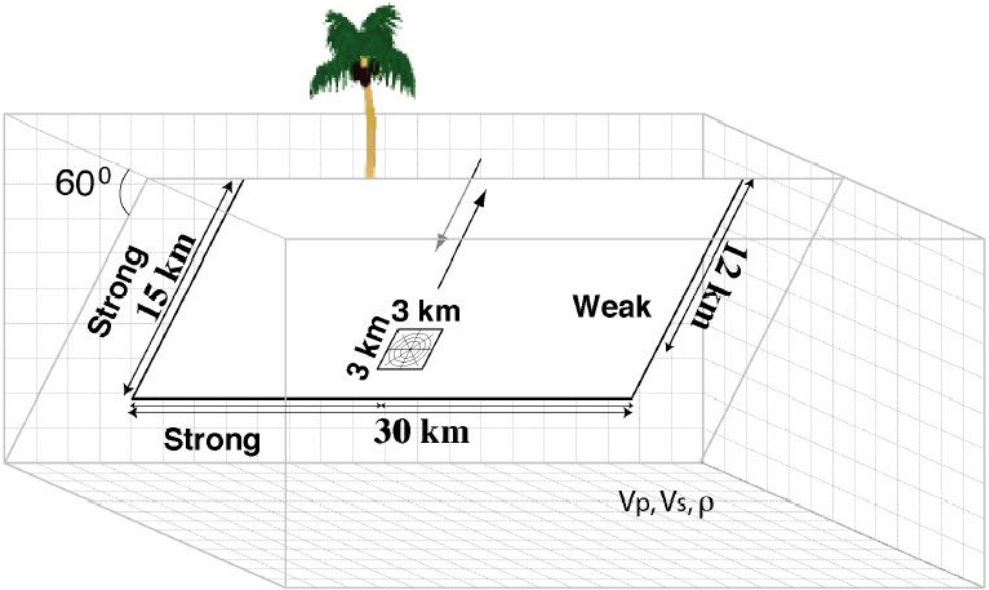
local desktop/laptop, ParaView: simple shake map maximum value of all timesteps (~peak ground velocity)



Examples 2,3 - geometrically simple and complex 3D dynamic rupture modeling

seismic wave propagation non-linearly coupled to frictional failure following linear slip weakening and fast velocity weakening friction laws and to off-fault plastic deformation

TPV 13 community benchmark
a dipping fault with off-fault plasticity



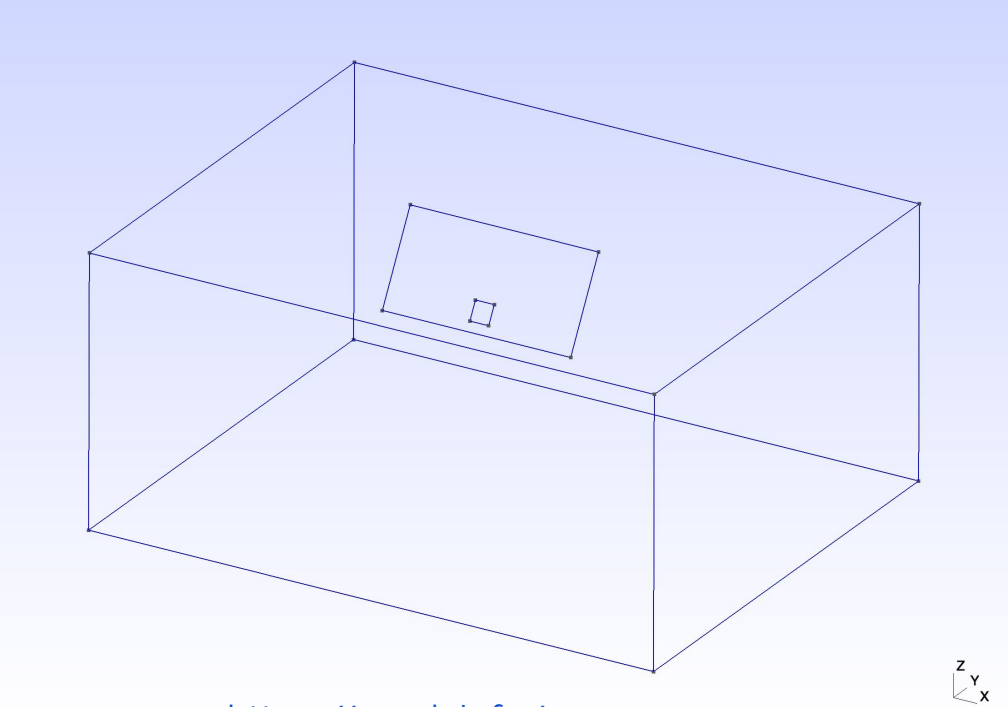
https://strike.scec.org/cvws/tpv12_13docs.html

Description of TPV13

- spontaneous rupture on a **60-degree dipping normal fault**
- geometry: 30 by 15 km planar fault interface
- **homogeneous half-space**: Vp=5716 m/s, Vs=3300 m/s, rho=2700 km/m^3
- **non-associative Drucker-Prager plasticity**
- linear-slip weakening friction (LSW)
- initial stress conditions are **depth-dependent**
- **prescribed nucleation** zone: square, 1.5 km size
- **supershear** initial conditions (ratio of fault strength to initial loading)

GMSH .geo file - geometry

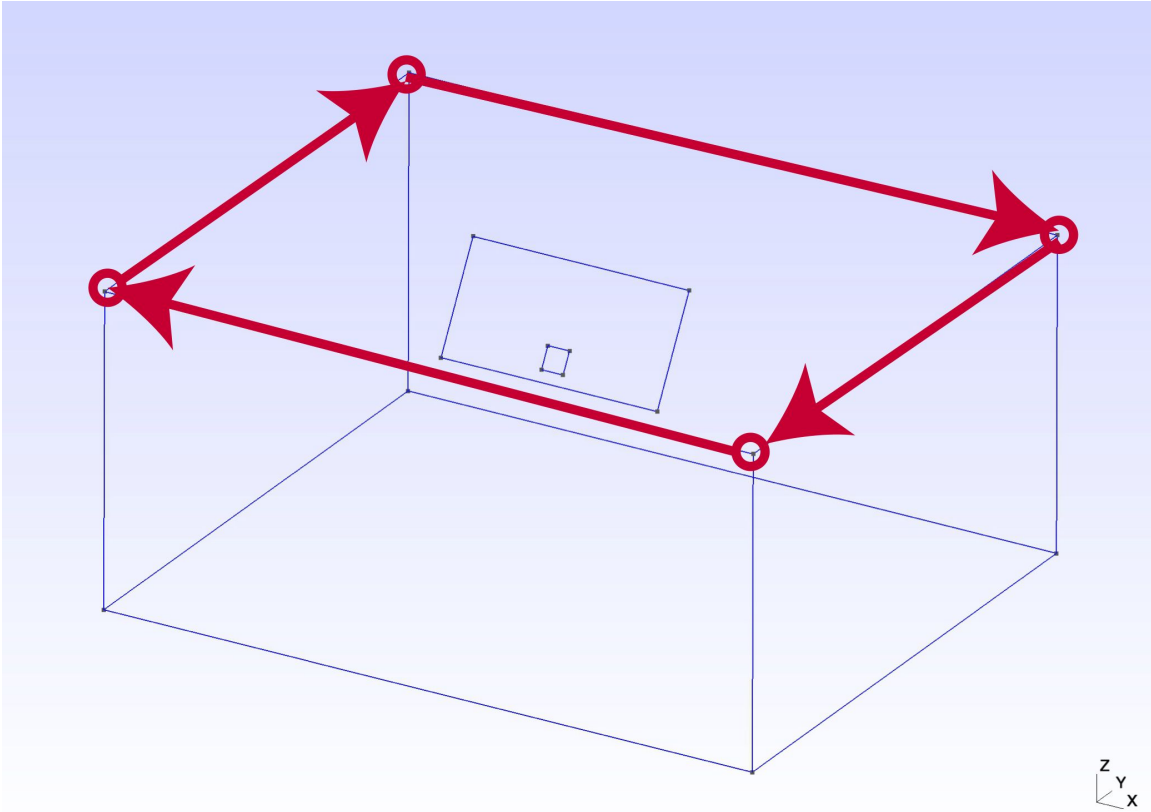
```
//resolution off- and on-fault and prescribing a nucleation region
lc = 25e3;              // maximum mesh size
lc_fault = 750;         // fault discretization
Fault_length = 30e3;
Fault_width = 15e3;
Fault_dip = 60*Pi/180.;
// volume size: 3-4 times of the fault's dimension
Xmax = 45e3;
Xmin = -Xmax;
Ymin = 36e3;
Ymax =  -Ymin;
Zmin = -42e3;
```



<https://gmsh.info/>

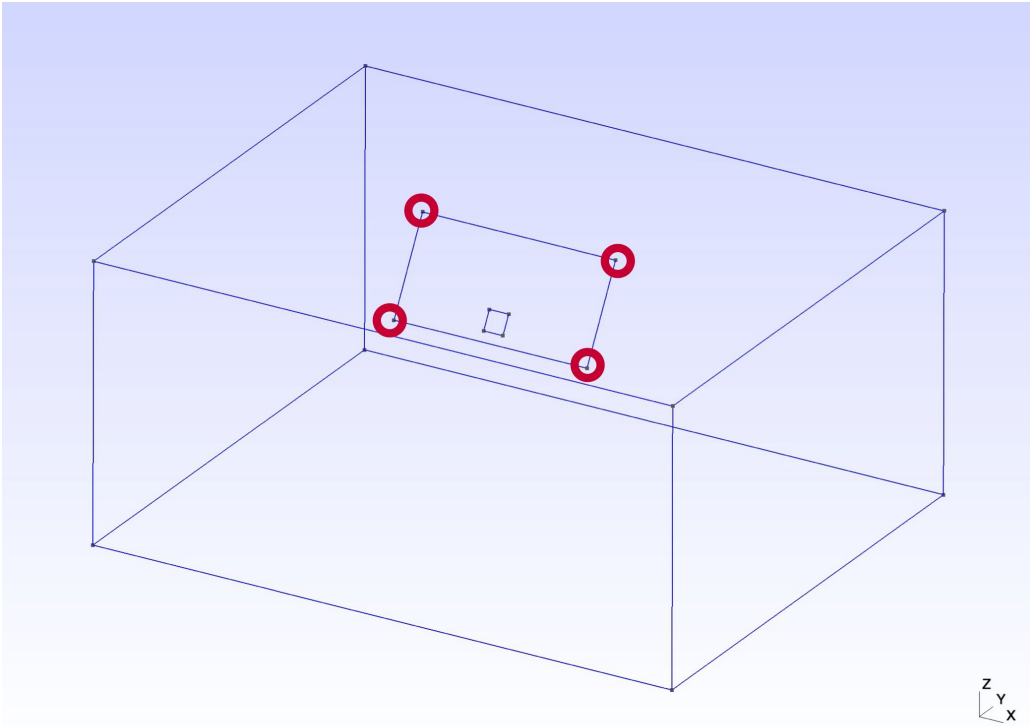
GMSH .geo file

```
//create the Volume
//points -> lines -> surface
Point(1) = {Xmin, Ymin, 0, lc};
Point(2) = {Xmin, Ymax, 0, lc};
Point(3) = {Xmax, Ymax, 0, lc};
Point(4) = {Xmax, Ymin, 0, lc};
Line(1) = {1, 2};
Line(2) = {2, 3};
Line(3) = {3, 4};
Line(4) = {4, 1};
Line Loop(5) = {1,2,3,4};
Plane Surface(1) = {5};
Extrude {0,0, Zmin} { Surface{1}; }
```



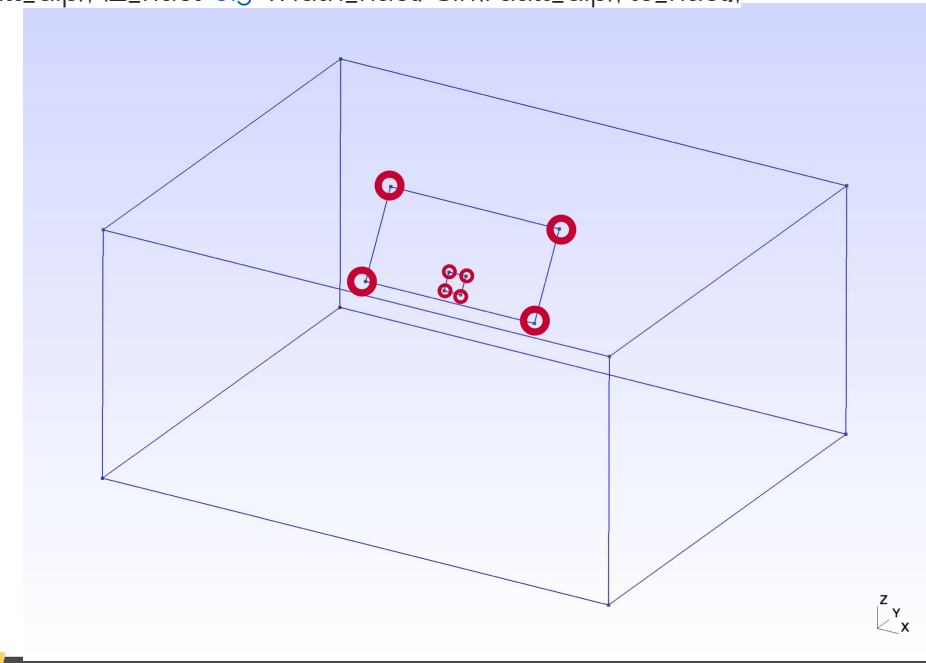
GMSH .geo file

```
//create the fault
Point(100) = {-0.5*Fault_length, -Fault_width
*Cos(Fault_dip), -Fault_width  *Sin(Fault_dip), lc};
Point(101) = {-0.5*Fault_length, 0, 0e3, lc};
Point(102) = {0.5*Fault_length, 0,  0e3, lc};
Point(103) = {0.5*Fault_length, -Fault_width
*Cos(Fault_dip), -Fault_width  *Sin(Fault_dip), lc};
Line(100) = {100, 101};
Line(101) = {101, 102};
Line{101} In Surface{1};
Line(102) = {102, 103};
Line(103) = {103, 100};
```



GMSH .geo file

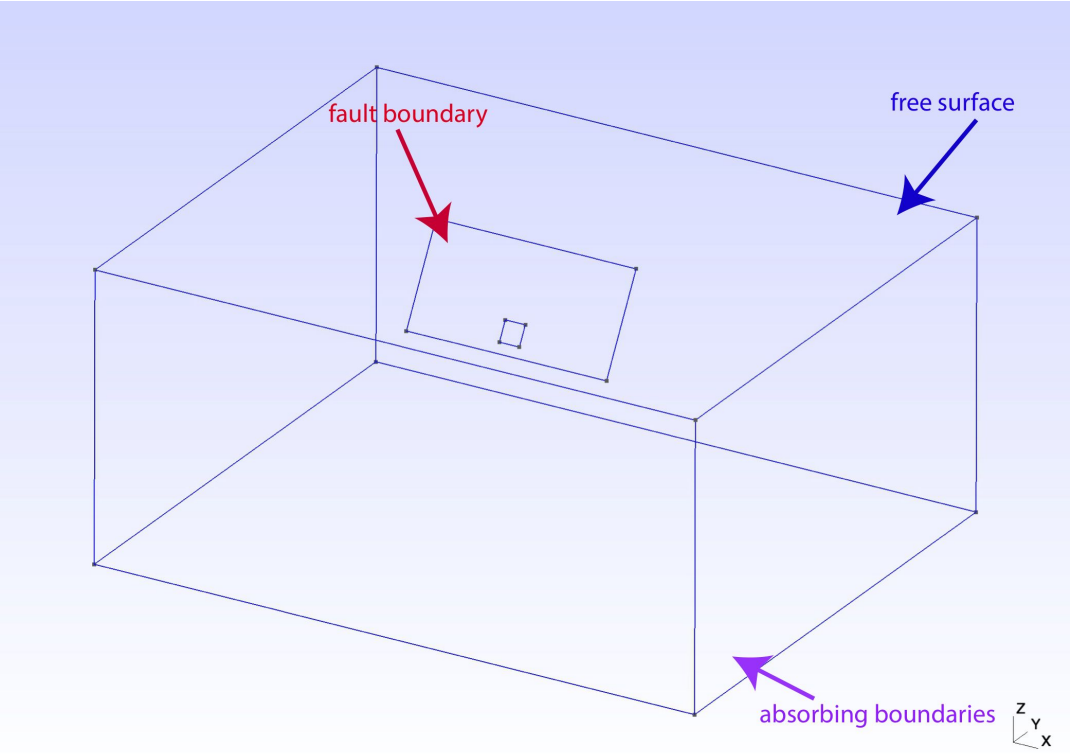
```
//create nucleation patch
Point(200) = {X_nucl + 0.5*Width_nucl, (Z_nucl+0.5*Width_nucl)*Cos(Fault_dip), (Z_nucl+0.5*Width_nucl)*Sin(Fault_dip), lc_nucl};
Point(201) = {X_nucl - 0.5*Width_nucl, (Z_nucl+0.5*Width_nucl)*Cos(Fault_dip), (Z_nucl+0.5*Width_nucl)*Sin(Fault_dip), lc_nucl};
Point(202) = {X_nucl - 0.5*Width_nucl, (Z_nucl-0.5*Width_nucl)*Cos(Fault_dip), (Z_nucl-0.5*Width_nucl)*Sin(Fault_dip), lc_nucl};
Point(203) = {X_nucl + 0.5*Width_nucl, (Z_nucl-0.5*Width_nucl)*Cos(Fault_dip), (Z_nucl-0.5*Width_nucl)*Sin(Fault_dip), lc_nucl};
Line(200) = {200,201};
Line(201) = {201,202};
Line(202) = {202,203};
Line(203) = {203,200};
Line Loop(204) = {200,201,202,203};
Plane Surface(200) = {204};

Line Loop(105) = {100,101,102,103,200,201,202,203};
Plane Surface(100) = {105};
```



GMSH .geo file

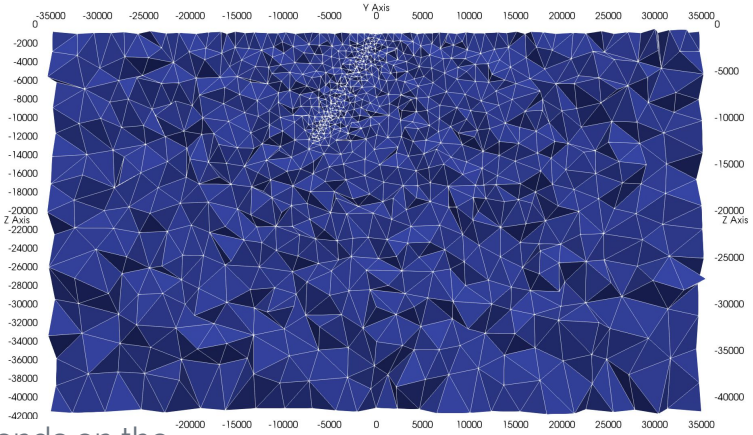
```
//define boundary conditions
//free surface
Physical Surface(101) = {1};
//fault boundary
Physical Surface(103) = {100,200};
//absorbing boundaries
Physical Surface(105) = {14,18,22,26,27};

Physical Volume(1) = {1};
Mesh.MshFileVersion = 2.2;
```

https://seissol.readthedocs.io/en/latest/gmsh.html#boundary-conditions



GMSH .geo file

```
// 1.2 coarsening away from the fault
// we can use two fields:
//  "Distance": returns distance to surface 101
Field[1] = Distance;
Field[1].FacesList = {101};   //identification of  fault surface


// secondly we can then create a `MathEval' field with a function that depends on the
// return value of the `Distance' field 1, i.e., depending on the distance to
//surface 101 (here Matheval field returns  "distance squared + lc/20")
Field[2] = MathEval;
Field[2].F = Sprintf("0.05*F1 +(F1/2.5e3)^2 + %g", lc_fault);


// refer to Gmsh tutorial  <https://gmsh.info/doc/texinfo/gmsh.html#t10>
// or SeisSol documentation: <https://seissol.readthedocs.io/en/latest/gmsh.html>
```



Fault coarsening in Paraview

parameters.par

```
&equations
MaterialFileName = 'tpv13_material.yaml'        ! include material parameter.
Plasticity = 1                                  ! off-fault plasticity, purely elastic = 0
Tv = 0.03                                       ! viscoplastic relaxation time
/

&Boundaries
BC_fs = 1                    ! free surface boundary condition
BC_dr = 1                    ! dynamic rupture fault boundary condition
BC_of = 1                    ! absorbing boundary condition
/
```

for more details look at: https://seissol.readthedocs.io/en/latest/tpv13.html

tpv13_material.yaml

```
!Switch
[rho, mu, lambda, plastCo, bulkFriction]: !ConstantMap
  map:
    rho:            2700
    mu:         2.9403e+010
    lambda:       2.941e+010
    plastCo:        5.0e+06
    bulkFriction:      0.85
[s_xx, s_yy, s_zz, s_xy, s_yz, s_xz]: !Include tpv13_initial_stress.yaml
```

tpv13_initial_stress.yaml

```
!Switch
[s_xx, s_yy, s_zz]: !FunctionMap
 map:
  depth: return abs(z);
  s_max_minus_Pf: return 9.8 * (2700.0 - 1000.0);
 components:
  # Upper region (includes fault)
  - !AxisAlignedCuboidalDomainFilter
   limits:
    depth:          [0, 11951.15]
    s_max_minus_Pf: [-.inf, .inf]
   components: !FunctionMap
    map:
     # Round to two significant digits as in benchmark description
     s_xx: return -0.01 * round(100.0 * (0.5 * (1.0 + 0.3496) * s_max_minus_Pf)) *
depth;
     s_yy: return -0.01 * round(100.0 *          (0.3496 * s_max_minus_Pf)) *
depth;
     s_zz: return -s_max_minus_Pf * depth;
  # Lower region (excludes fault)
  - !FunctionMap
   map:
    s_xx: return -s_max_minus_Pf * depth;
    s_yy: return -s_max_minus_Pf * depth;
    s_zz: return -s_max_minus_Pf * depth;
```

< https://easyinit.readthedocs.io/en/latest/maps.html#functionmap >

< https://easyinit.readthedocs.io/en/latest/filters.html >

Parameter	Value
above 11951.15 m	
σ_1	26460 Pa/m * H
σ_3	15624.3 Pa/m * H
σ_2	$(\sigma_1 + \sigma_3)/2$
P_f	$1000kg/m^3 * 9.8m/s^2 * H$
below 11951.15 m	
$\sigma_1, \sigma_2, \sigma_3$	$2700kg/m^3 * 9.8m/s^2 * H$

<https://strike.scec.org/cvws/tpv12_13docs.html>

parameters.par

```
&DynamicRupture
FL = 2                                  ! FL=2: use linear-slip weakening friction law
ModelFileName = 'tpv13_fault.yaml'

XRef = 0.0                              ! Reference point
YRef = -1.0
ZRef = 0.0
OutputPointType = 5
! Type (0 : no output; 3 : ASCII fault receivers; 4 : paraview file; 5 : both)
/
```

<https://seissol.readthedocs.io/en/latest/parameter-file.html?highlight=reference%20point#reference-point>

tpv13_fault.yaml

```yaml
!Switch
[s_xx, s_yy, s_zz, s_xy, s_yz, s_xz]: !Include tpv13_initial_stress.yaml
[mu_s, mu_d, d_c, cohesion]: !IdentityMap
 components:
  # Inside nucleation patch
  - !AxisAlignedCuboidalDomainFilter
    limits:
      x: [-1500, 1500]
      y: [-.inf, .inf]
      z: [-11691.34295108992, -9093.266739736605]
    components: !ConstantMap
      map:
        mu_s:      0.4
        mu_d:      0.10
        d_c:       0.50
        cohesion: -200000
  # Outside nucleation patch
  - !ConstantMap
    map:
      mu_s:      0.70
      mu_d:      0.10
      d_c:       0.50
      cohesion: -200000
```

```
&Elementwise
printIntervalCriterion = 2                  ! 1=iteration, 2=time
printtimeinterval_sec = 0.5                 ! Time interval at which output will be written
OutputMask = 1 1 0 0 1 0 1 1 0 0 0  0       ! output 1/ yes, 0/ no - position:
refinement_strategy = 2                     ! triangles are split into 4 triangles
refinement = 2                              ! subdivides each triangle
/
```

OutputMask

https://seissol.readthedocs.io/en/latest/fault-output.html

1. **SRs and SRd**: slip rates in strike and dip direction
2. **T_s, T_d**: transient shear stress in strike and dip direction, **P_n**: transient normal stress
3. **U_n**: normal velocity (note that there is no fault opening in SeisSol)
4. **Mud**: current friction, **StV**: state variable in case of RS friction
5. **Tso,Tdo,Pno**: total stress, including initial stress
6. **Sls and Sld**: slip in strike and dip direction
7. **Vr**: rupture velocity, computed from the spatial derivatives of the rupture time
8. **ASl**: absolute slip
9. **PSR**: peak slip rate
10. **RT**: rupture time
11. **DS**: only with linear slip-weakening friction, time at which ASl>D_c
12. **P_f** and **Tmp**: pore fluid pressure and temperature for thermal pressurization

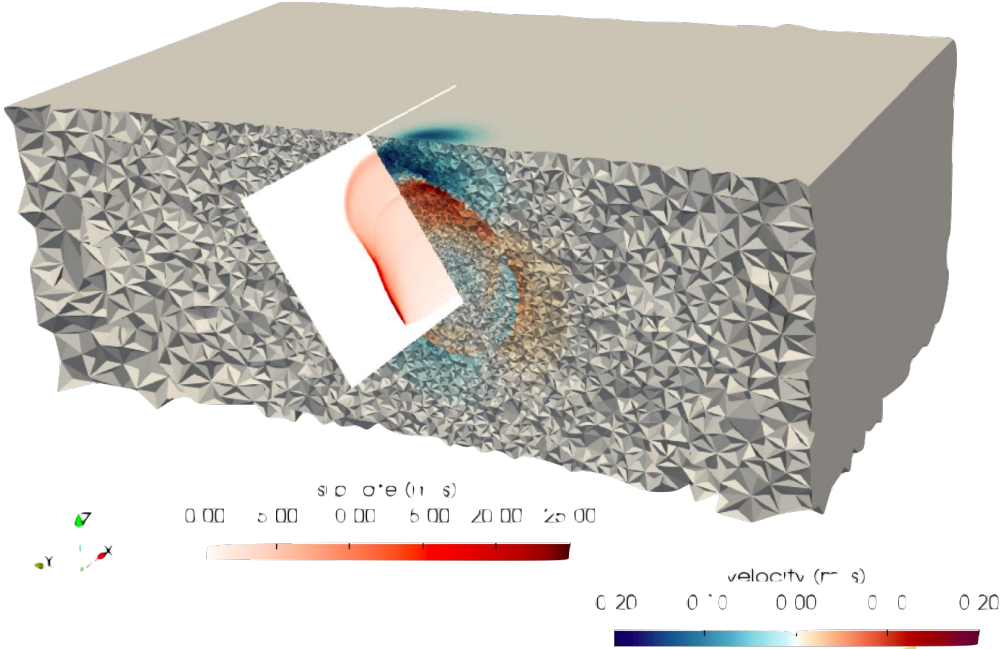
parameters.par

```
&MeshNml
MeshFile = 'tpv13_training_puml.h5'        ! Name of mesh file in HDF5 format
meshgenerator = 'PUML'                     ! Name of mesh generator
/

&Discretization
CFL = 0.5                                  ! The Courant-Friedrichs-Levy (CFL) Stability Criterion (<=1.0)
FixTimeStep = 5                            ! Manualy chosen minimum time
ClusteredLTS=2
! 1 for Global time stepping, 2,3,5,... Local time stepping (advised value 2)
! ClusteredLTS defines the multi-rate for the time steps of the clusters 2 for Local time stepping
/
```

parameters.par

```
&Output
OutputFile ='output/tpv13'
! output files will be generated inside a folder named 'output' and all output files have 'tpv13' prefix
/

&AbortCriteria
EndTime = 4.0                    ! run the simulation for 4 seconds
/
```

Hand's on! (25 minutes)



desktop/laptop: Create mesh

>> **Mac/Linux:**

```
$ ./training.sh gmsh -3 tpv13_training.geo

$ ./training.sh pumgen tpv13_training.msh -s msh2
```

>> **or Windows**

```
> docker run -v ${PWD}:/shared/ uphoffc/seissol-training gmsh -3 tpv13_training.geo

> docker run -v ${PWD}:/shared/ uphoffc/seissol-training pumgen tpv13_training.msh -s msh2
```

>> This will give you the mesh file **tpv13_training.puml.h5**

(**backup mesh**: /shared/cheese/seissol/setups/solution/tpv13_mesh/tpv13_training.puml.h5)

training cluster: submit job

Copy mesh to ~/work/TPV13/mesh

$ **qsub submit.sh**

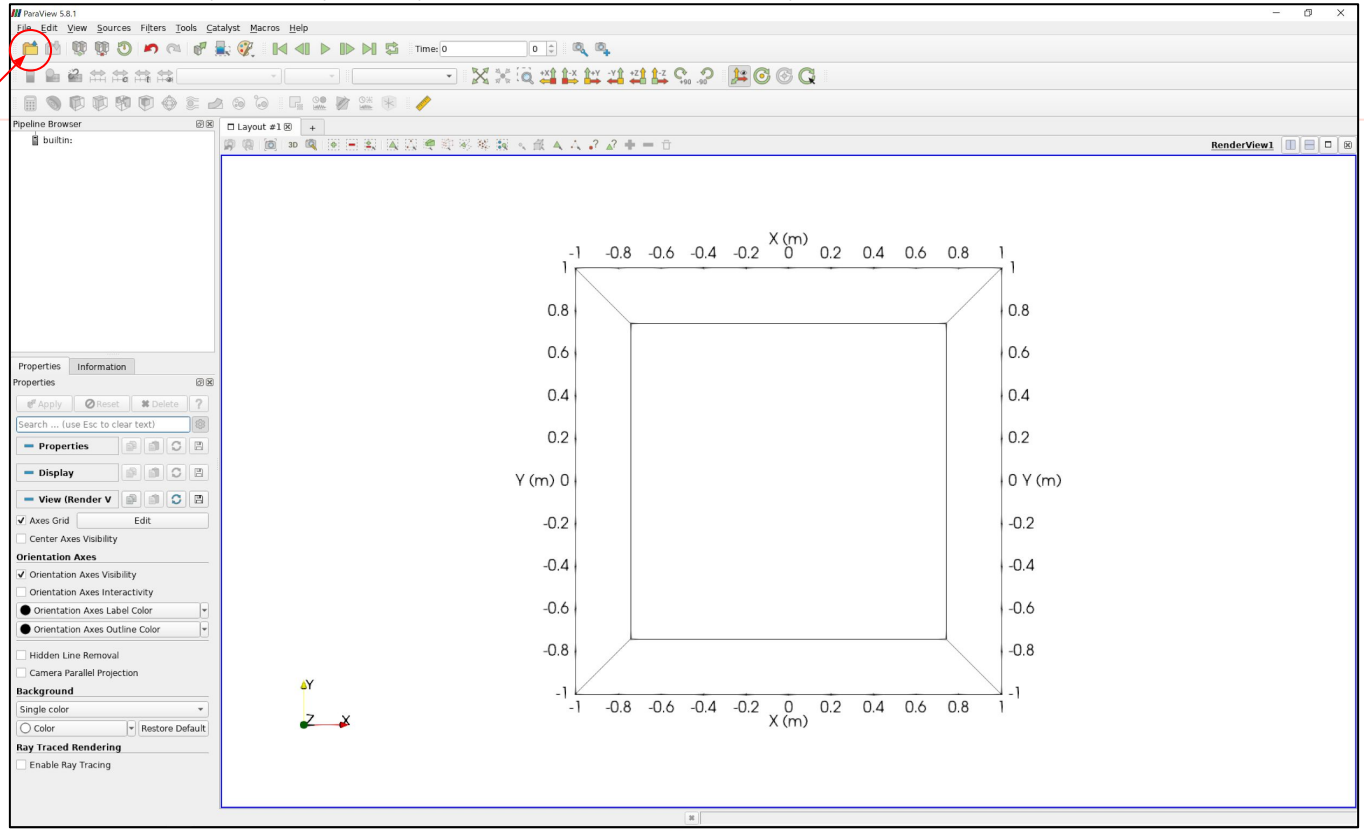
desktop/laptop: post-processing

- Copy output files from remote (HLRS) to local (desktop/laptop)
- In your terminal:

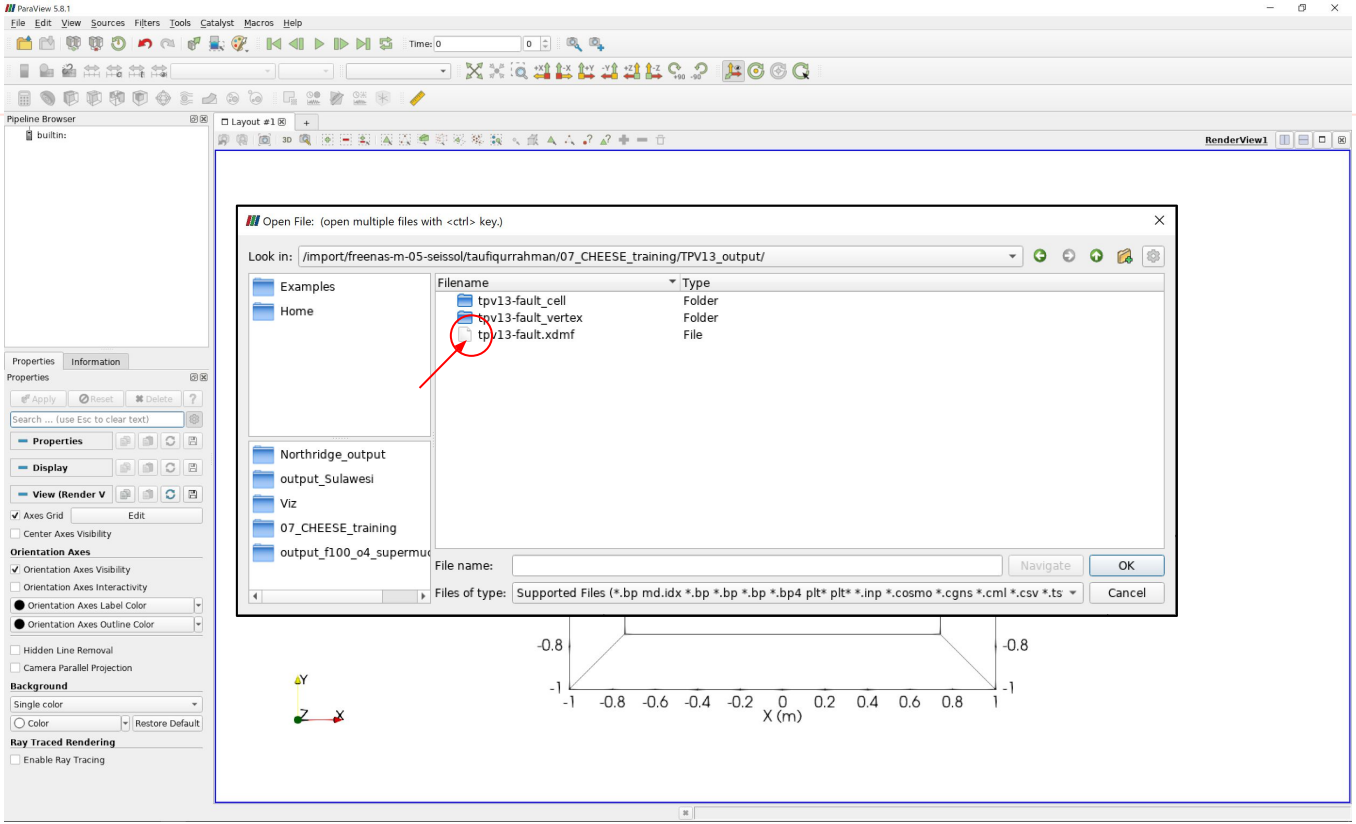
```
$ scp -r scaXXXXX@training.hlrs.de :work/TPV13 .
```

- We will use Paraview to visualize the fault output
- Back up output link: `/shared/cheese/seissol/output/TPV13/`

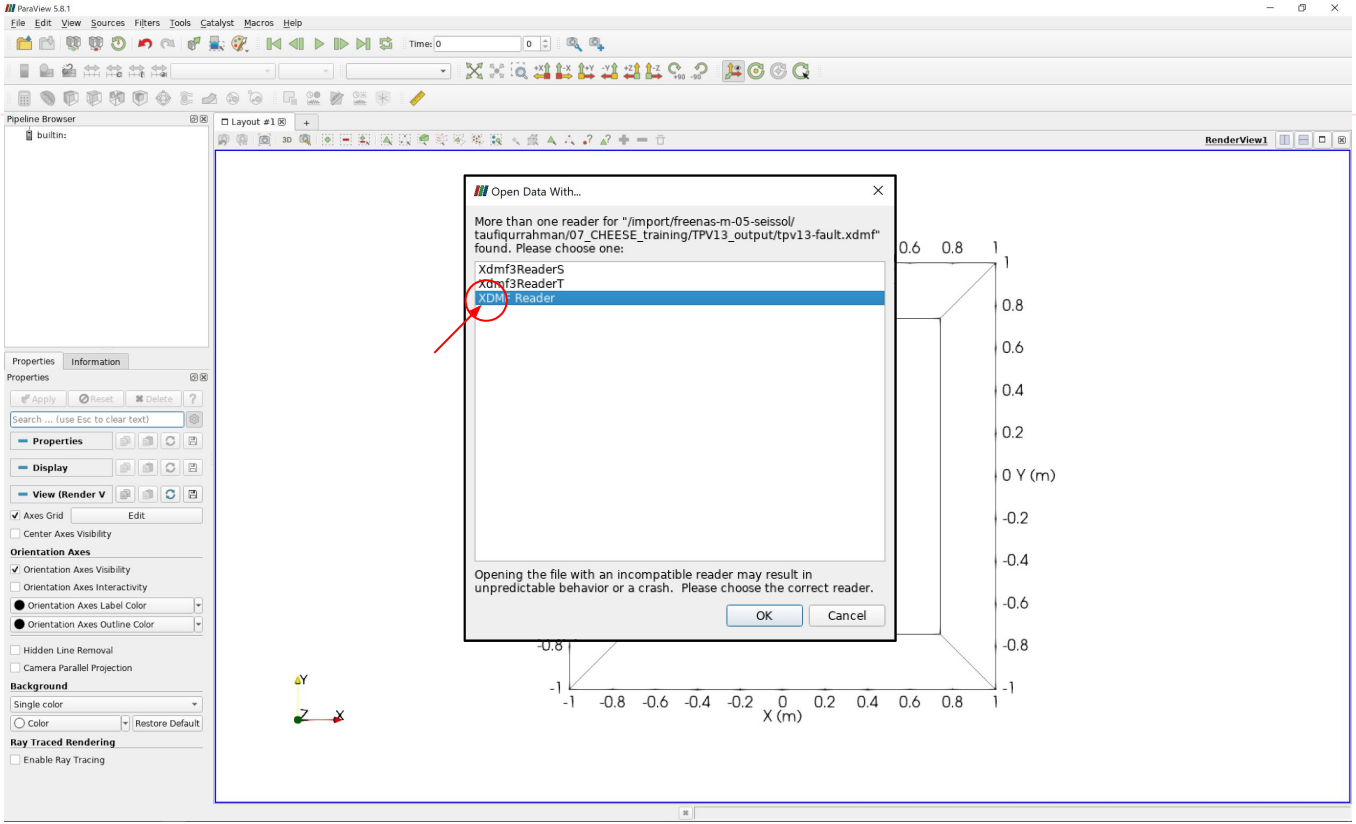
local desktop/laptop, Paraview: open file



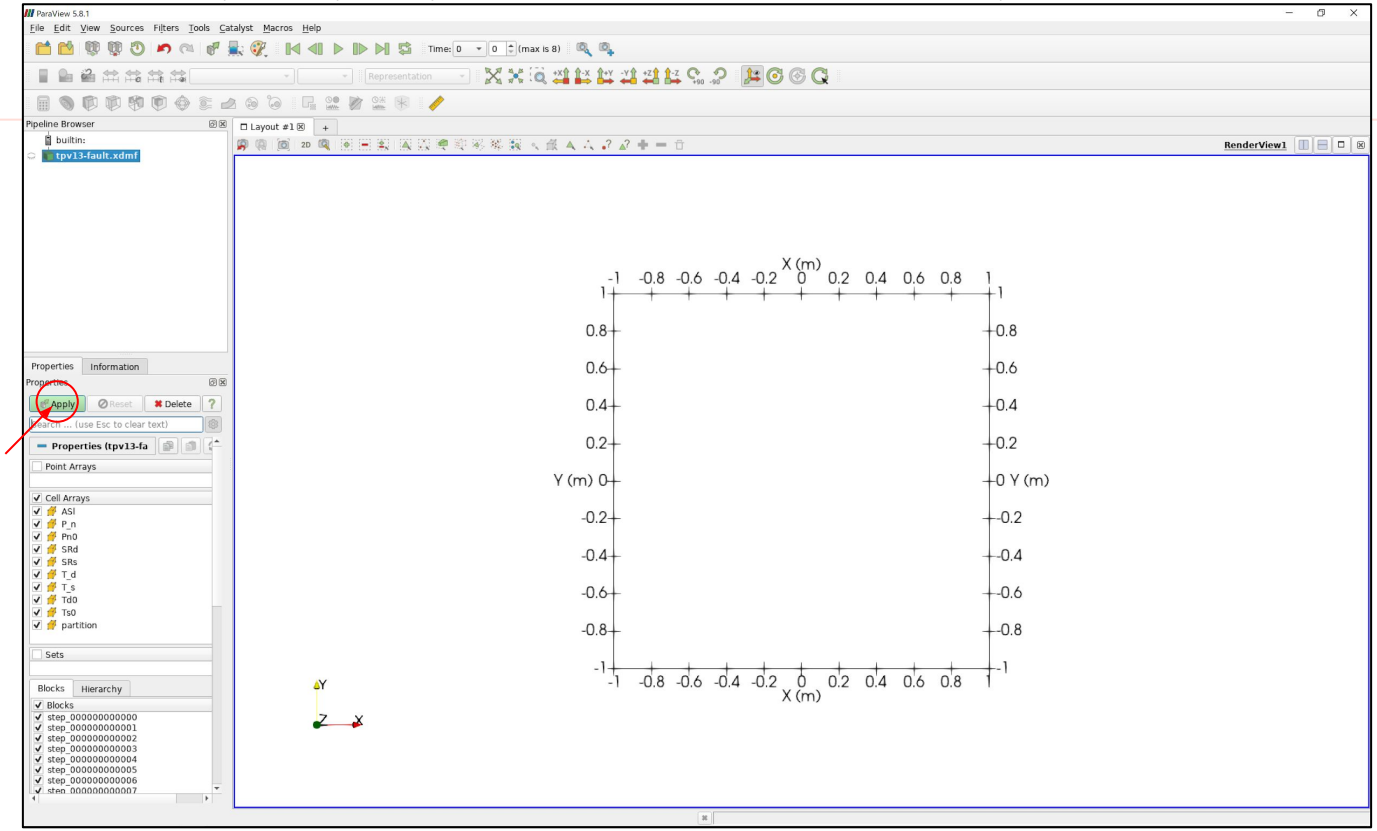
local desktop/laptop, Paraview: load output file



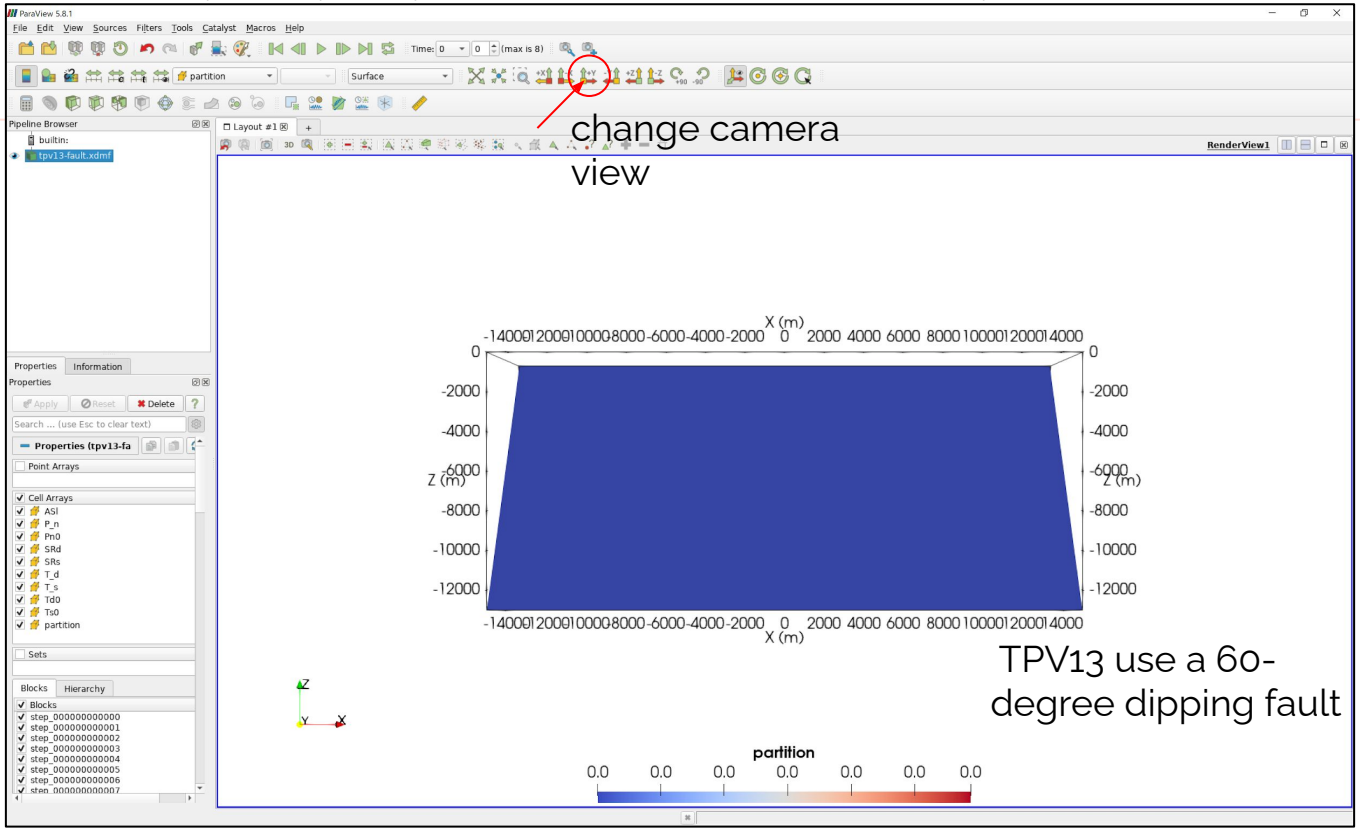
local desktop/laptop, Paraview: load output file



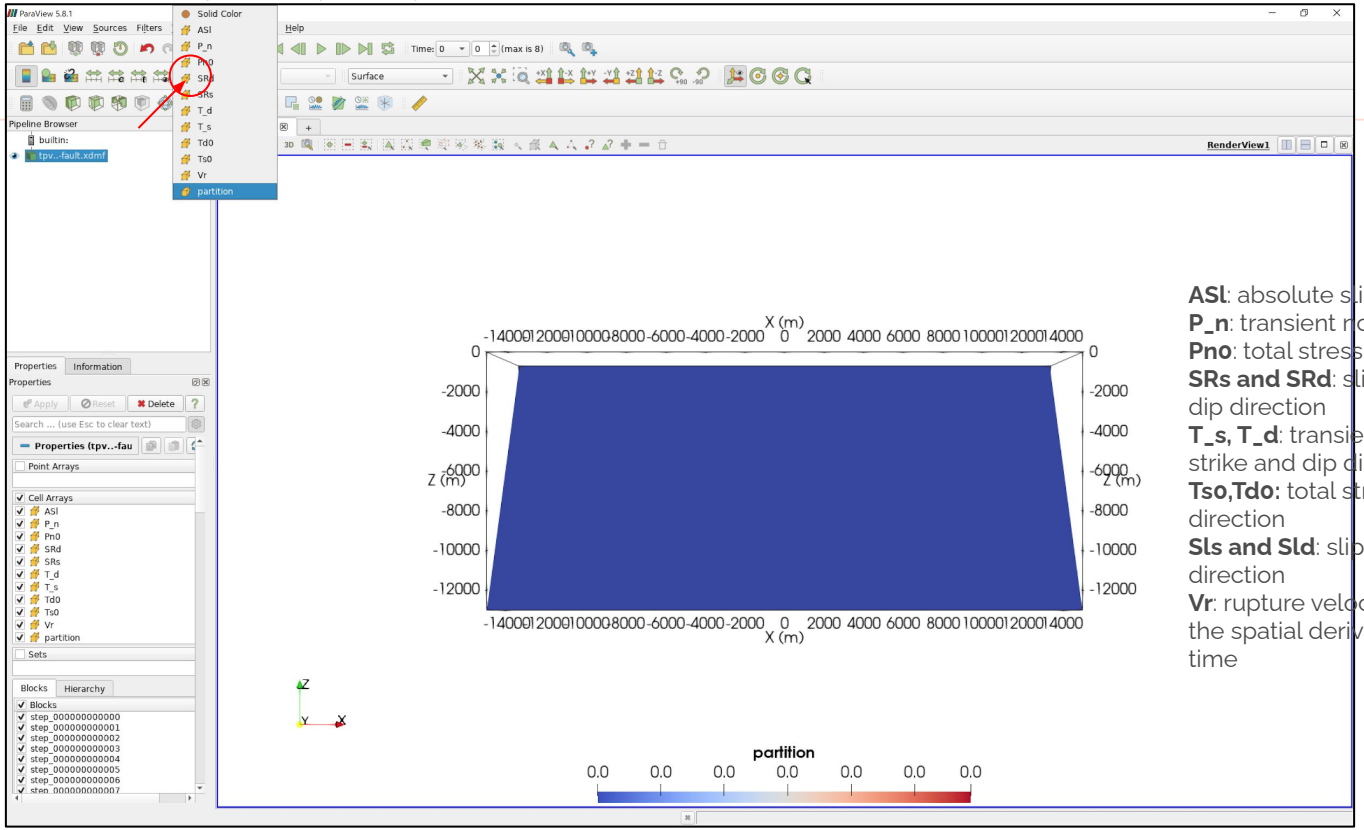
local desktop/laptop, Paraview: load output file



local desktop/laptop, Paraview: load output file



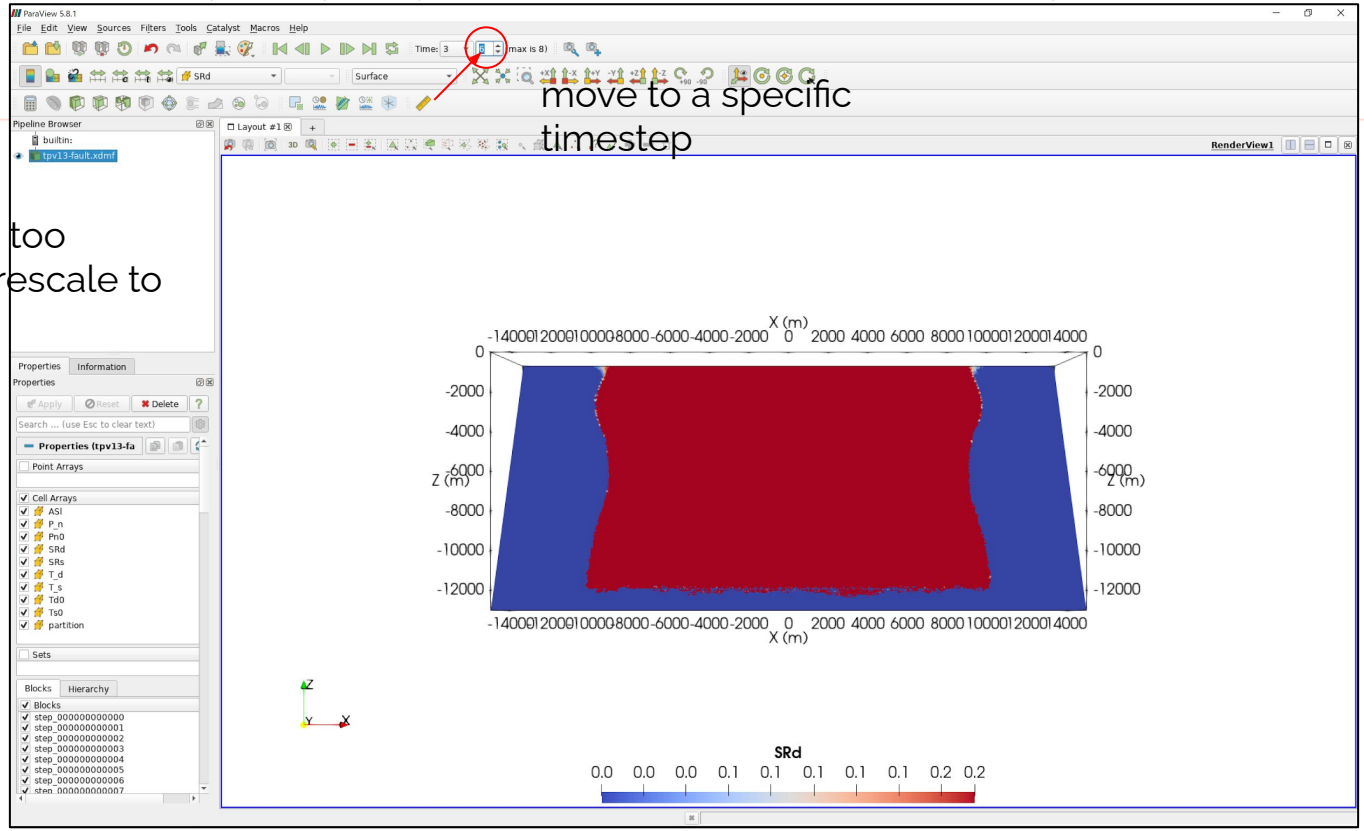
local desktop/laptop, Paraview: select a fault attribute



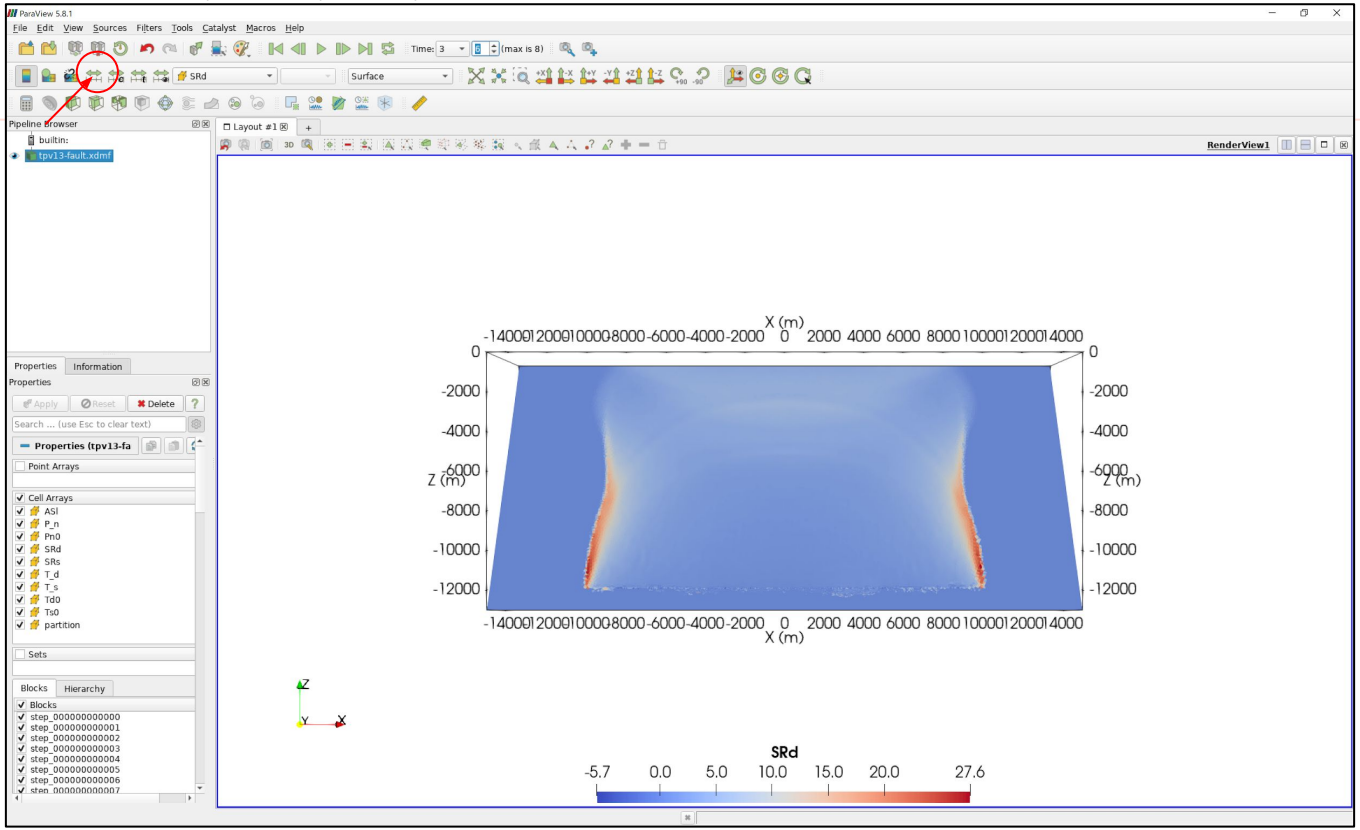
ASl: absolute slip
P_n: transient normal stress
Pno: total stress normal direction
SRs and SRd: slip rates in strike and dip direction
T_s, T_d: transient shear stress in strike and dip direction
Tso,Tdo: total stress in strike and dip direction
Sls and Sld: slip in strike and dip direction
Vr: rupture velocity, computed from the spatial derivatives of the rupture time

local desktop/laptop, Paraview: choose a specific time step

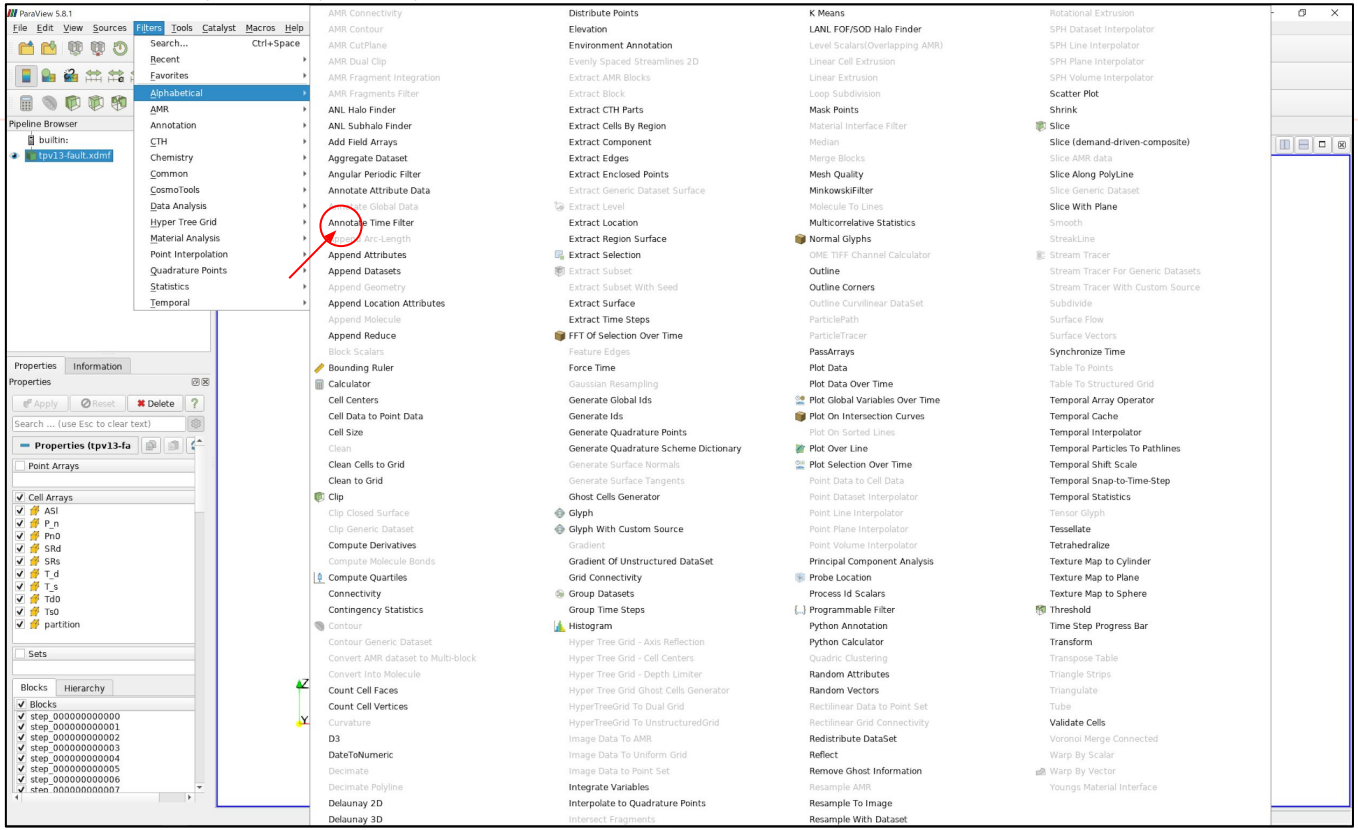
Data scale is too small, need rescale to data range



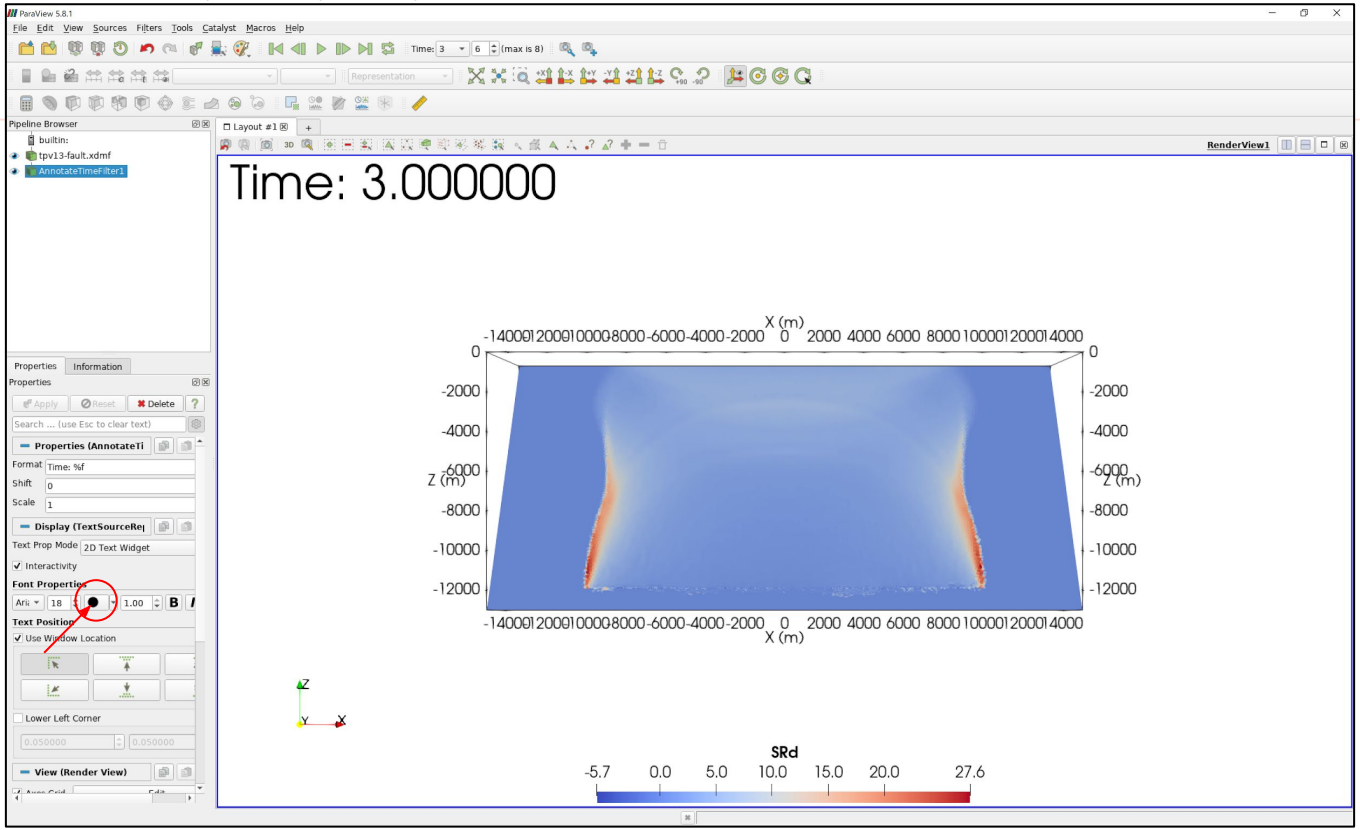
local desktop/laptop, Paraview: rescale to data range



local desktop/laptop, Paraview: add time annotation



local desktop/laptop, Paraview: add time annotation

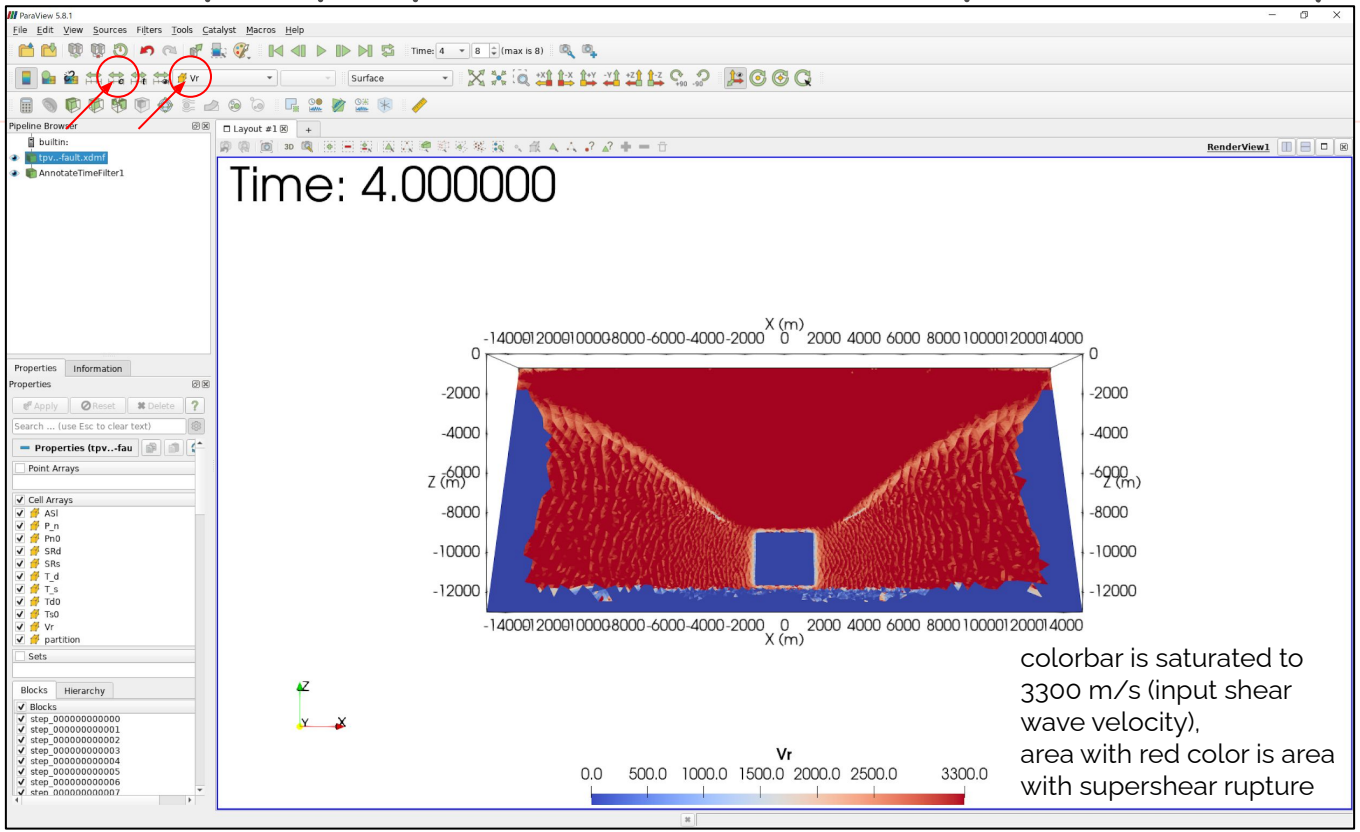


change time annotation font color

local desktop/laptop, Paraview: show rupture velocity

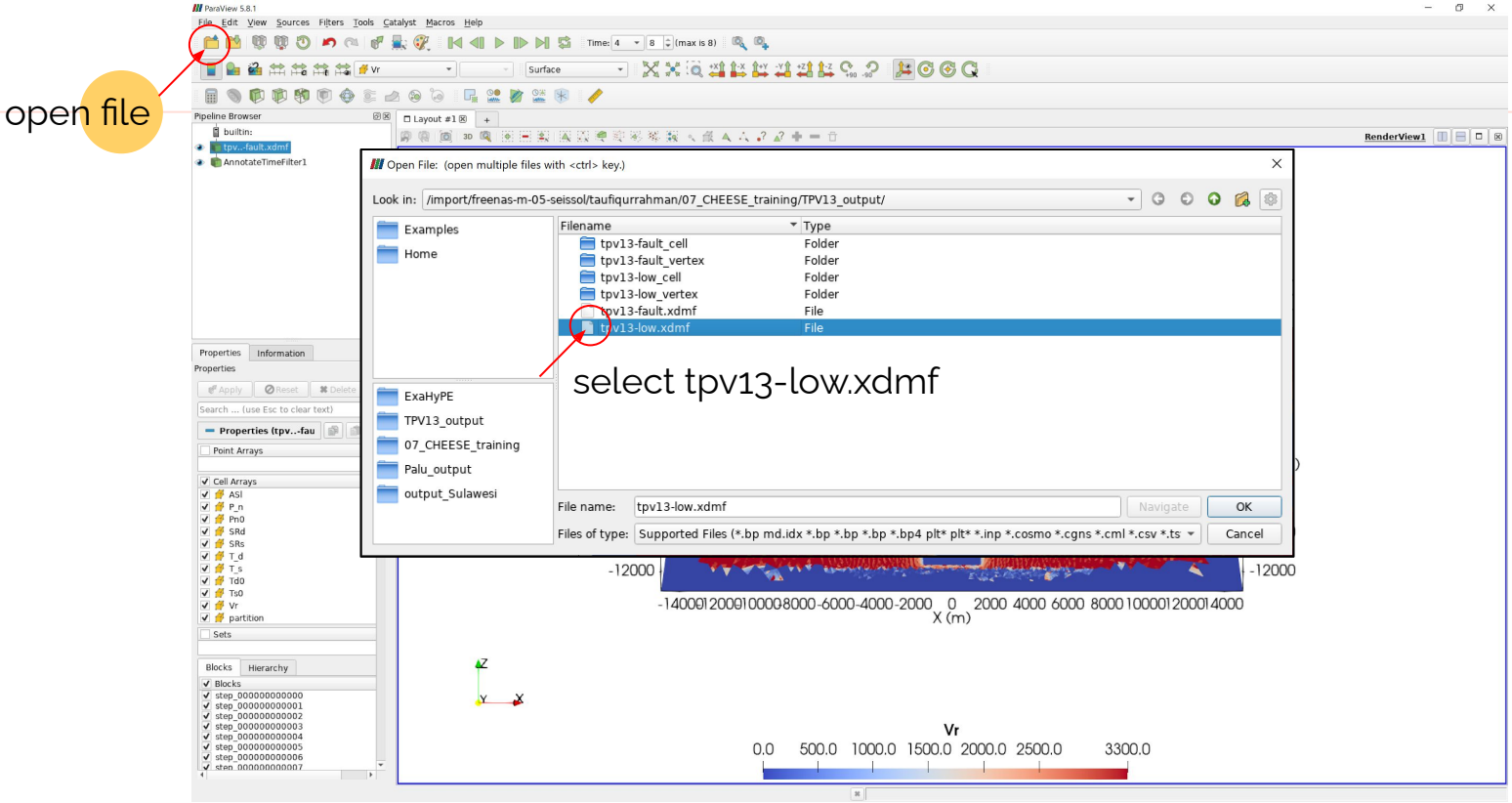
select attribute **Vr**

manually adjust data range from 0-3300 m/s

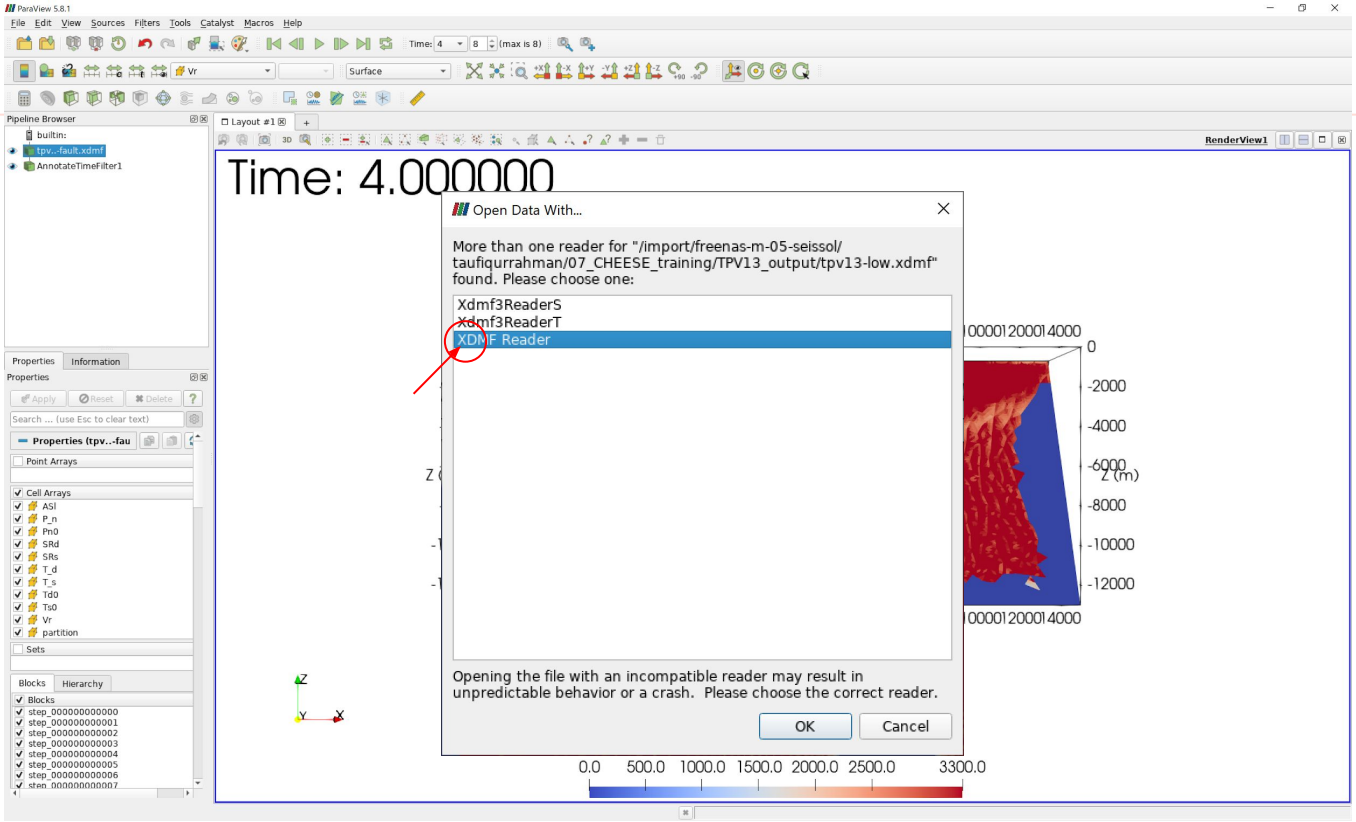


colorbar is saturated to 3300 m/s (input shear wave velocity),
area with red color is area with supershear rupture

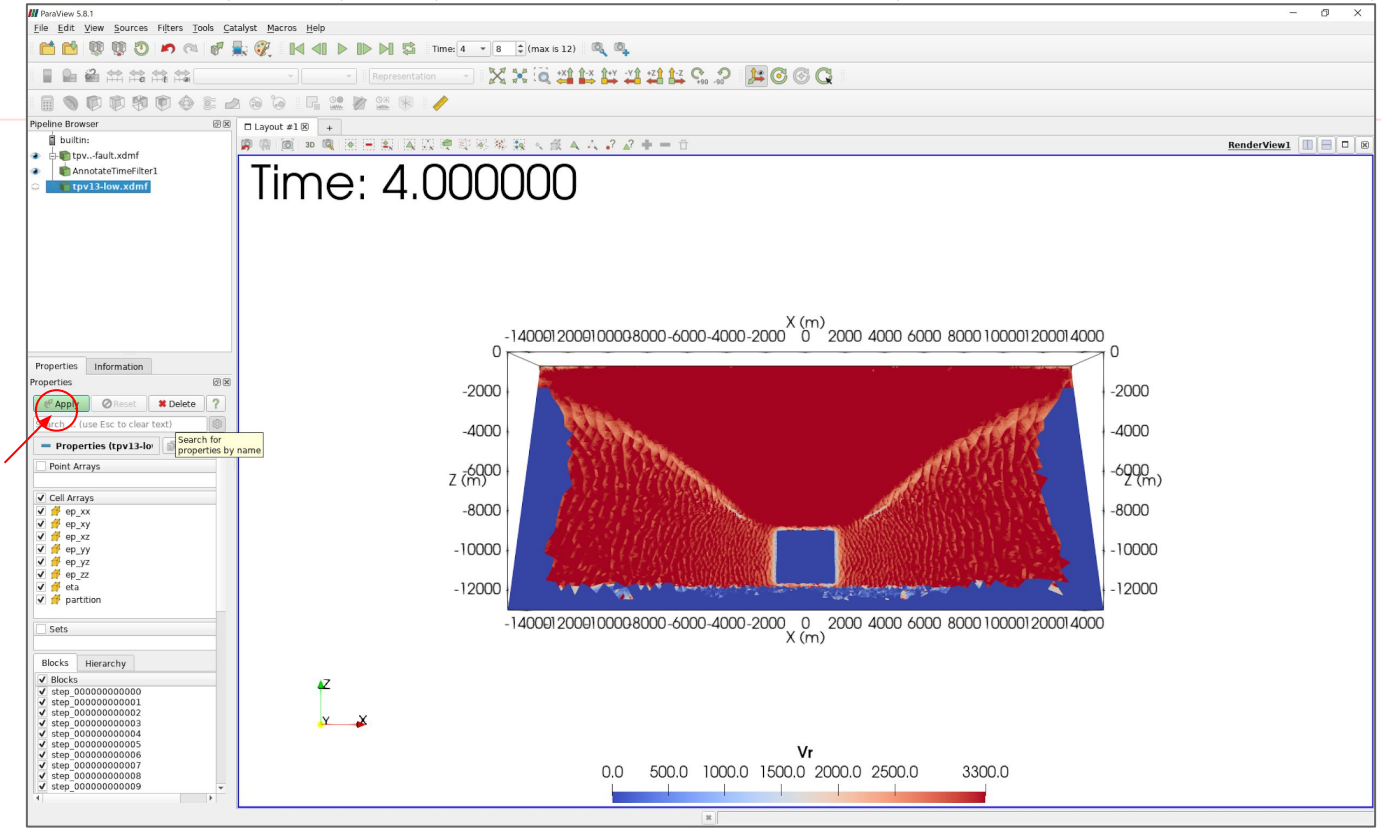
local desktop/laptop, Paraview: add plastic strain output



local desktop/laptop, Paraview: add plastic strain output

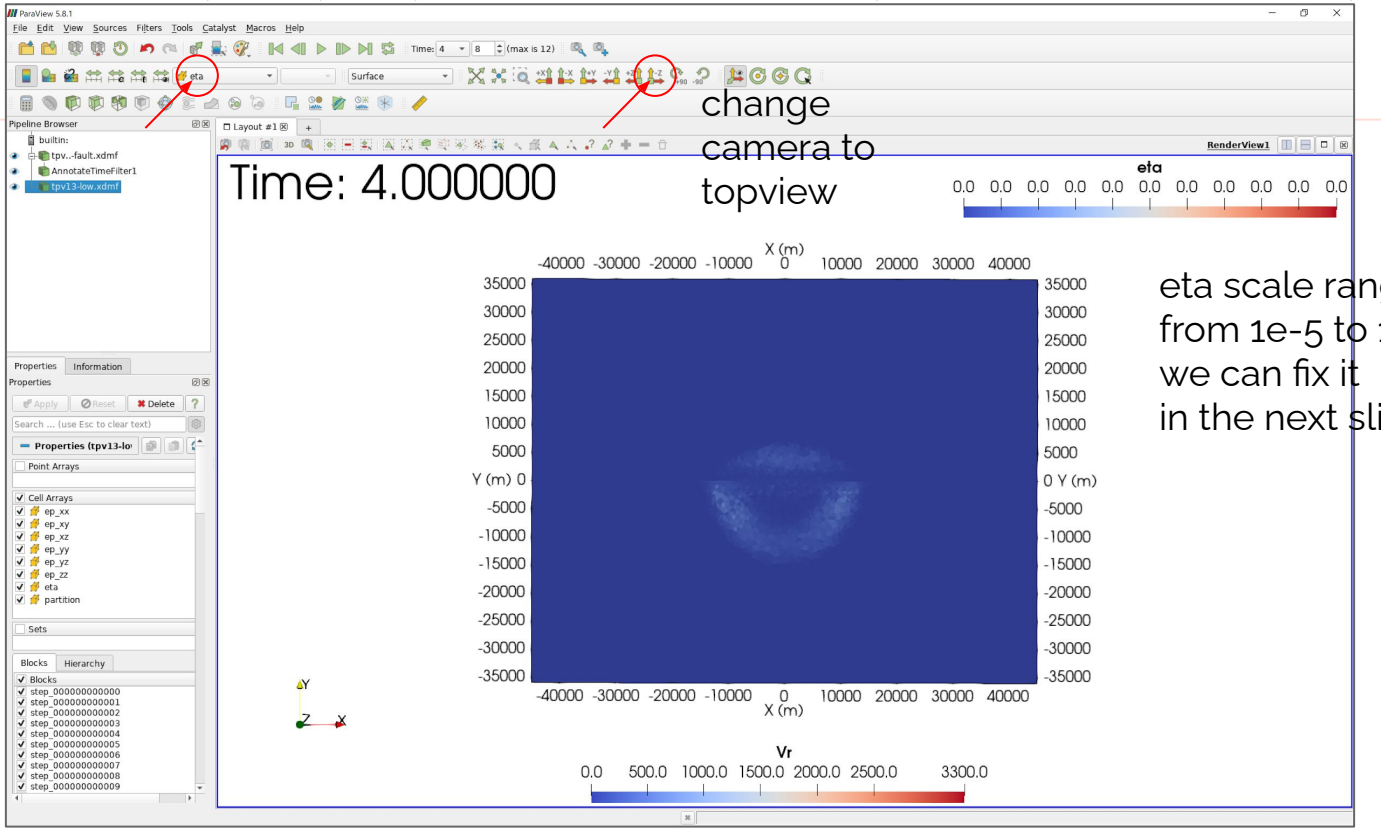


local desktop/laptop, Paraview: add plastic strain output



local desktop/laptop, Paraview: add plastic strain output

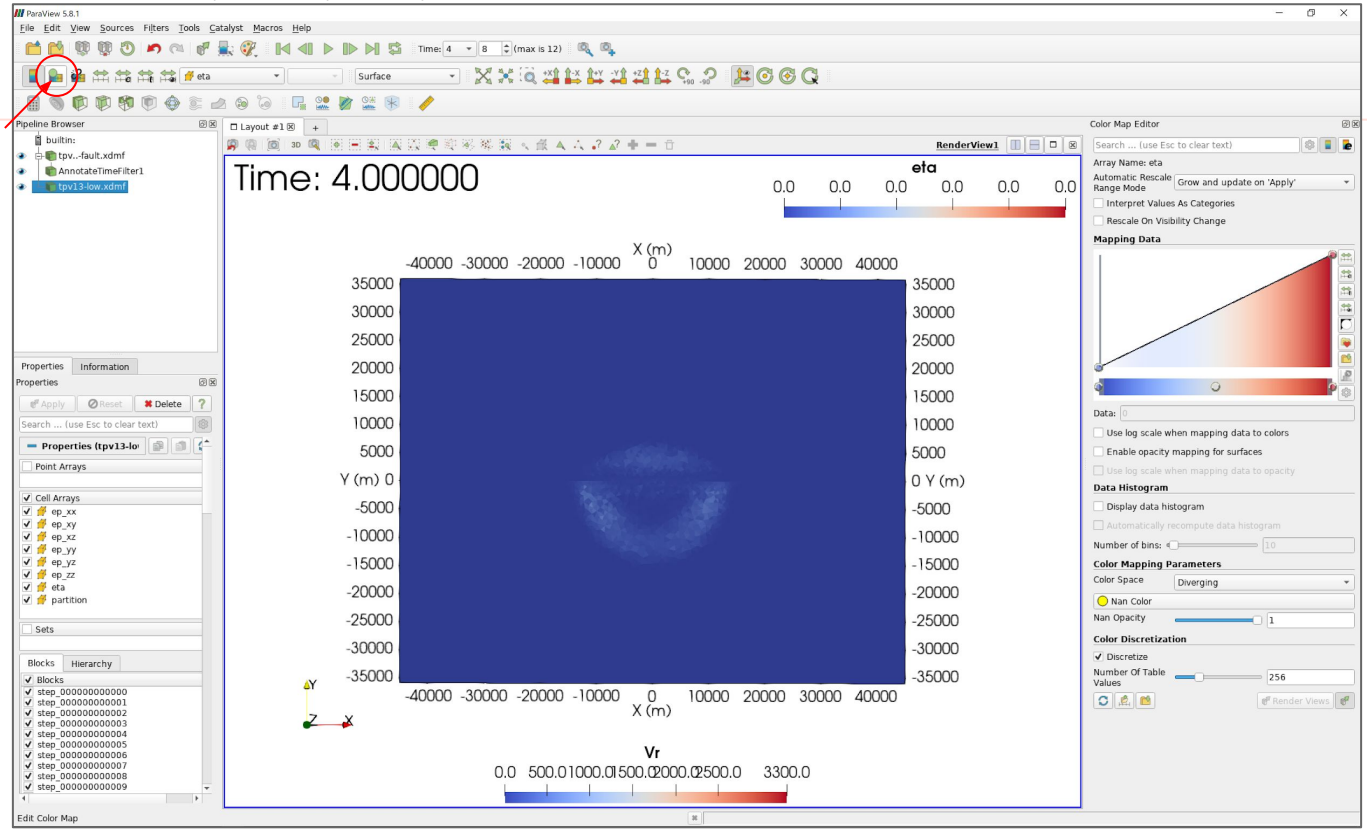
select attribute eta



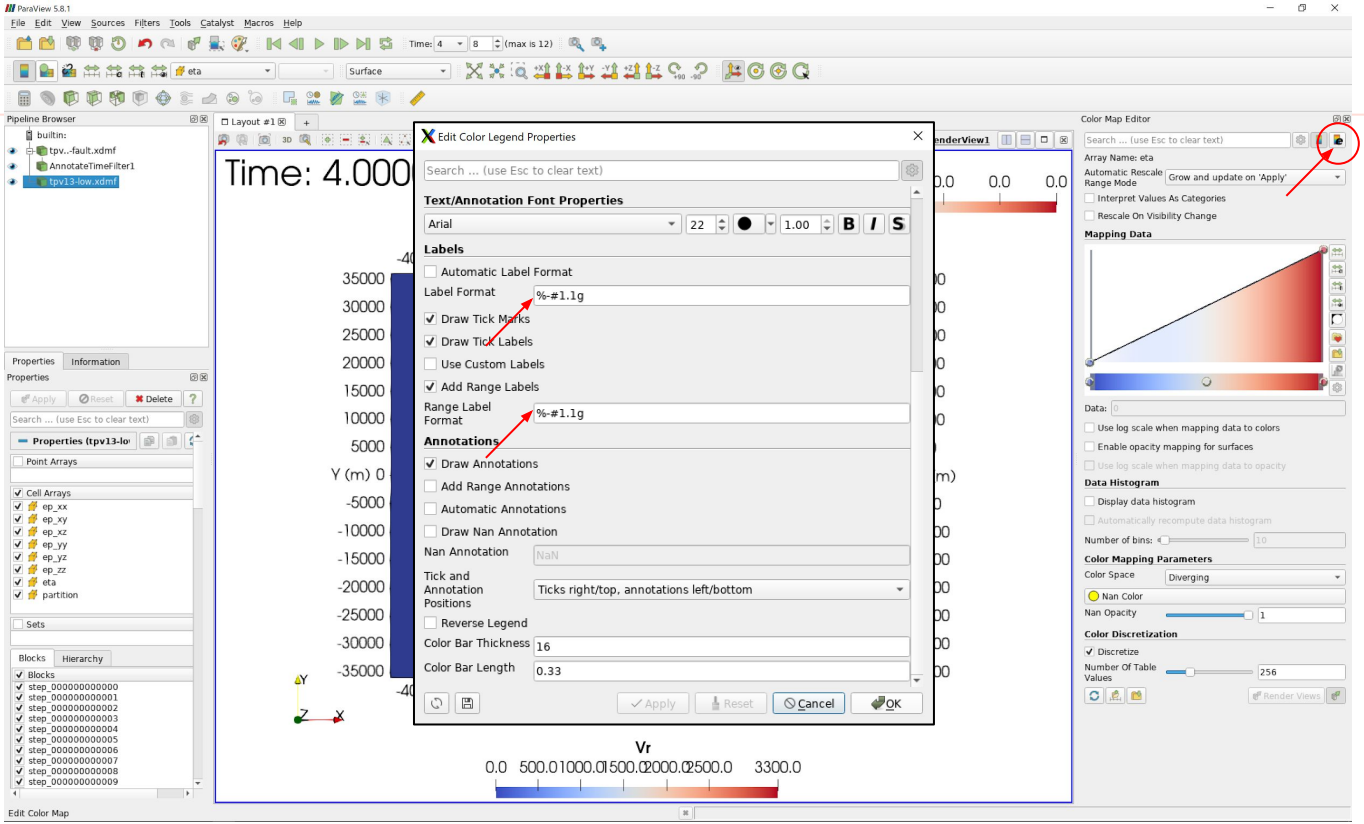
change camera to topview

eta scale range from 1e-5 to 1e-9, we can fix it in the next slide

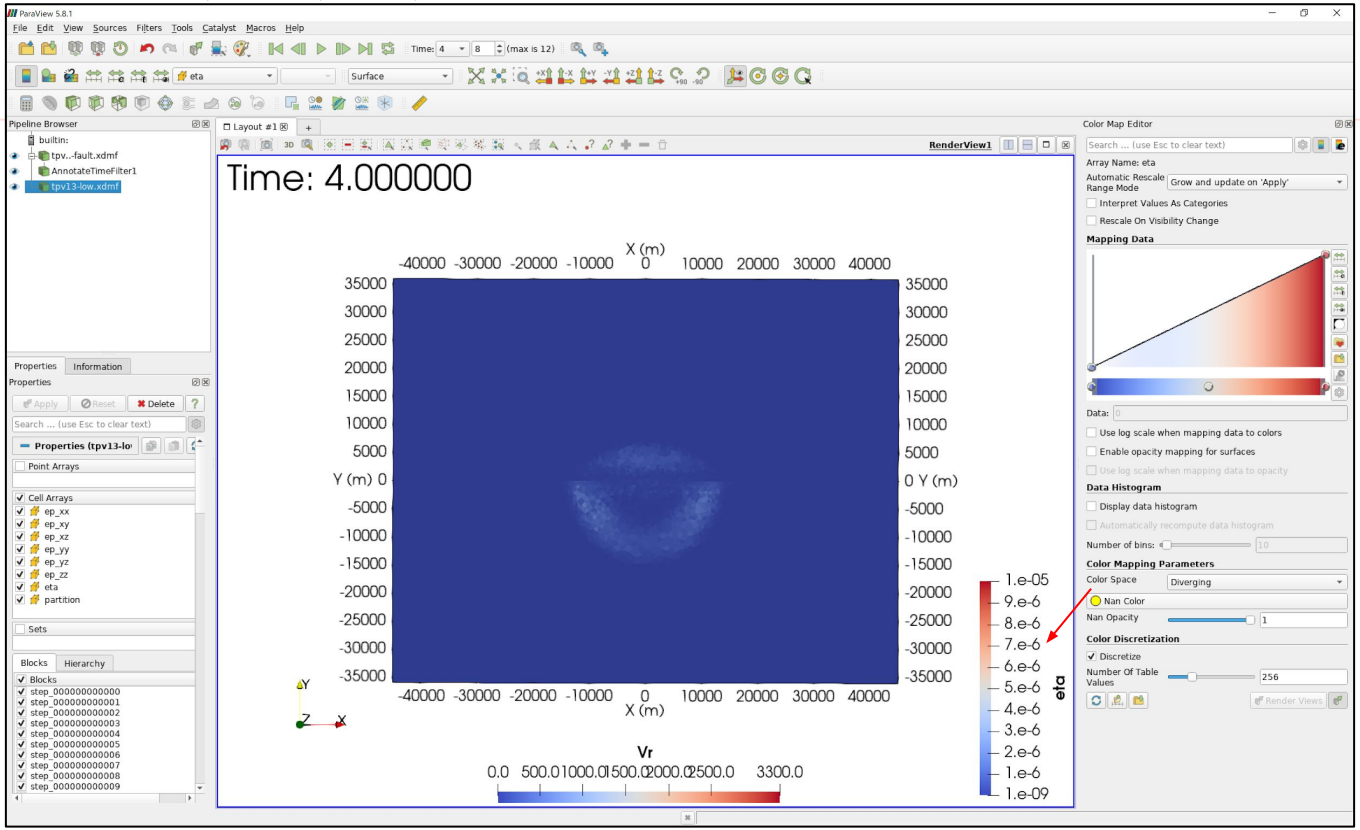
local desktop/laptop, Paraview: edit scalebar



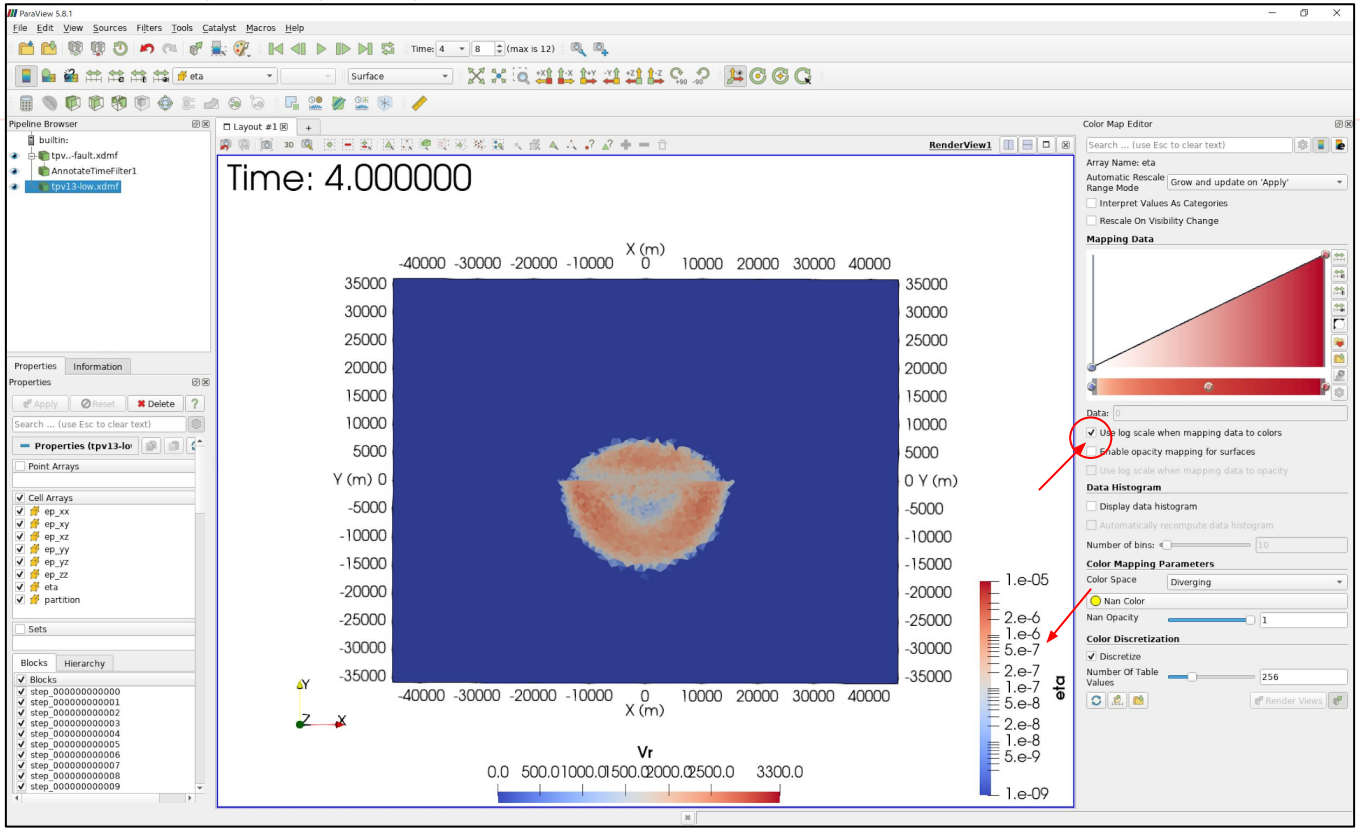
local desktop/laptop, Paraview: edit scalebar



local desktop/laptop, Paraview: edit scalebar

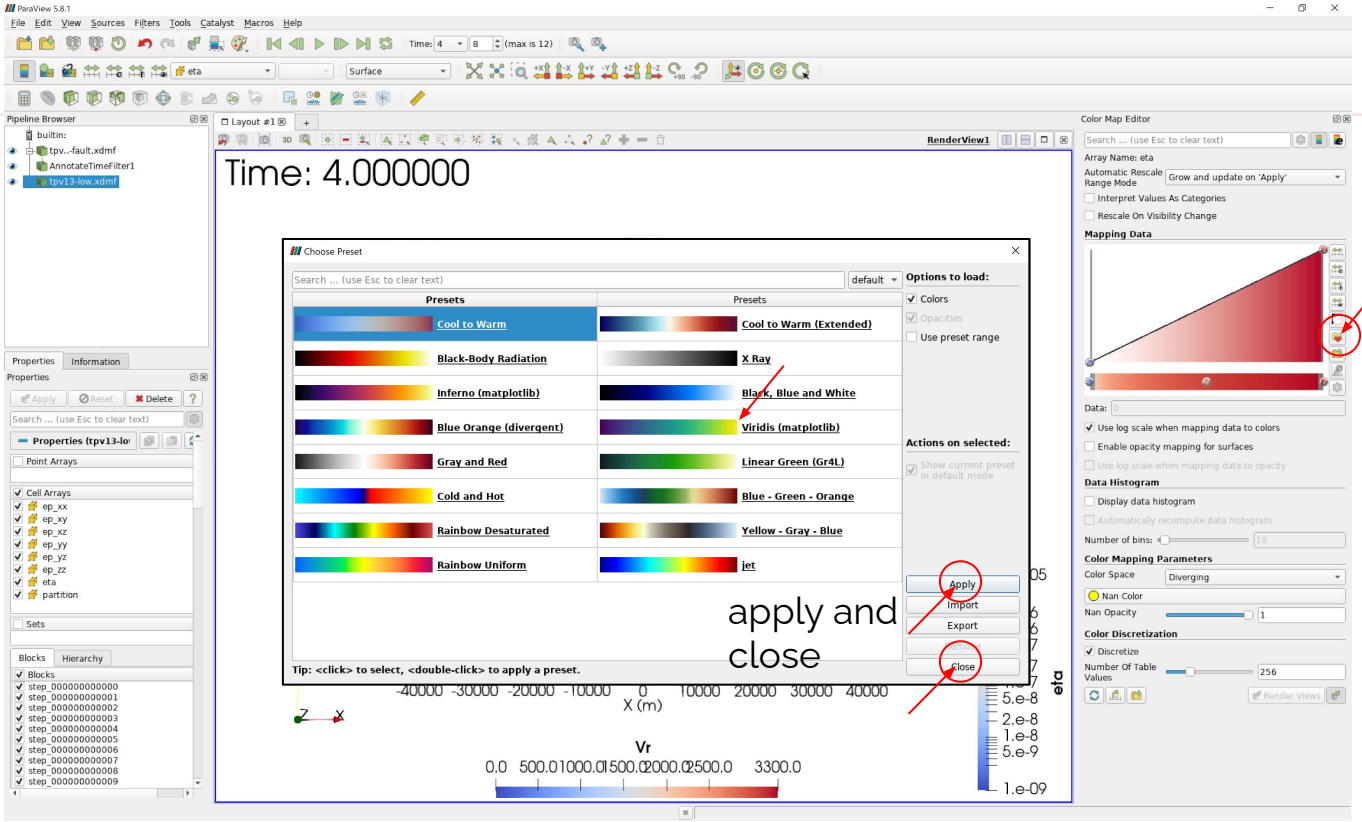


local desktop/laptop, Paraview: edit scalebar



change to log scale

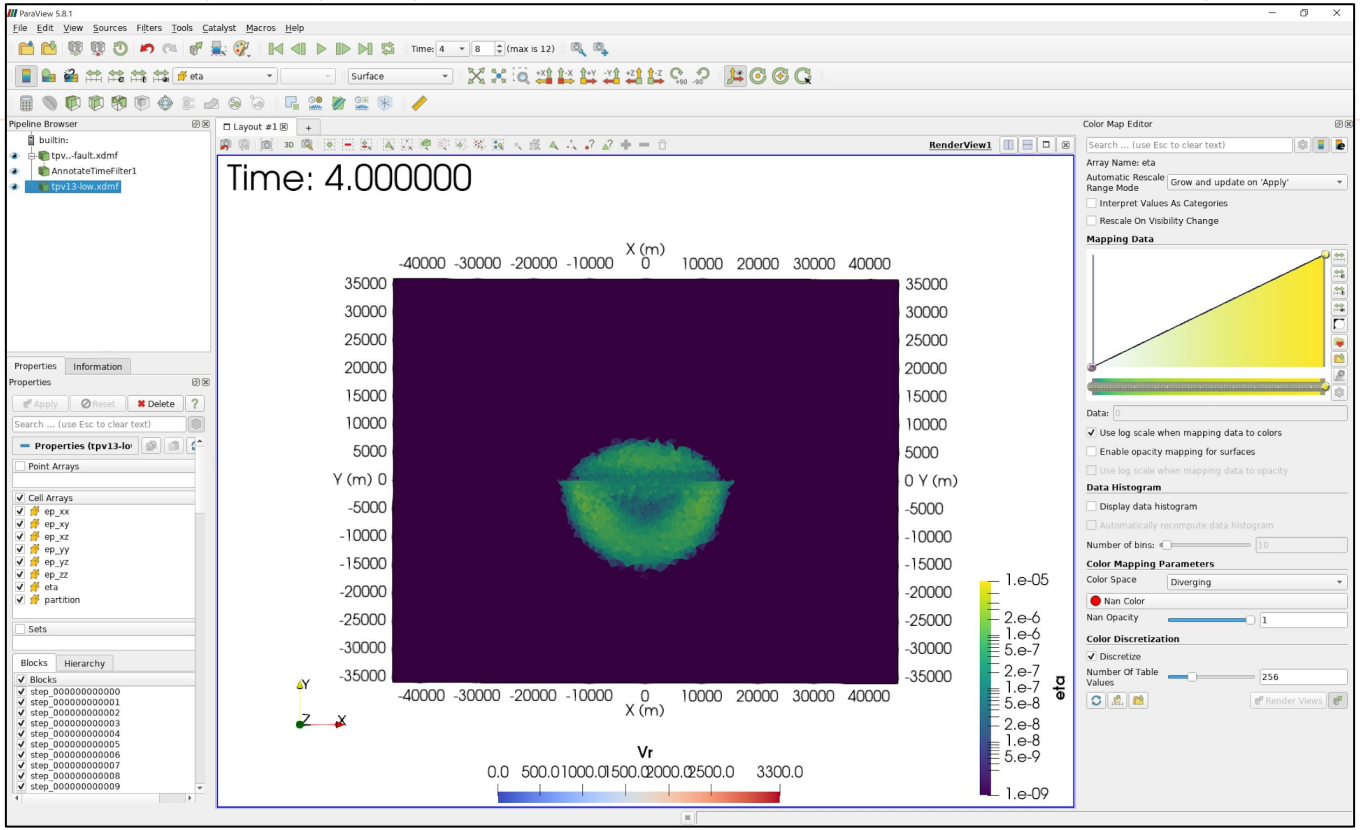
local desktop/laptop, Paraview: change colormap



choose preset colormap

apply and close

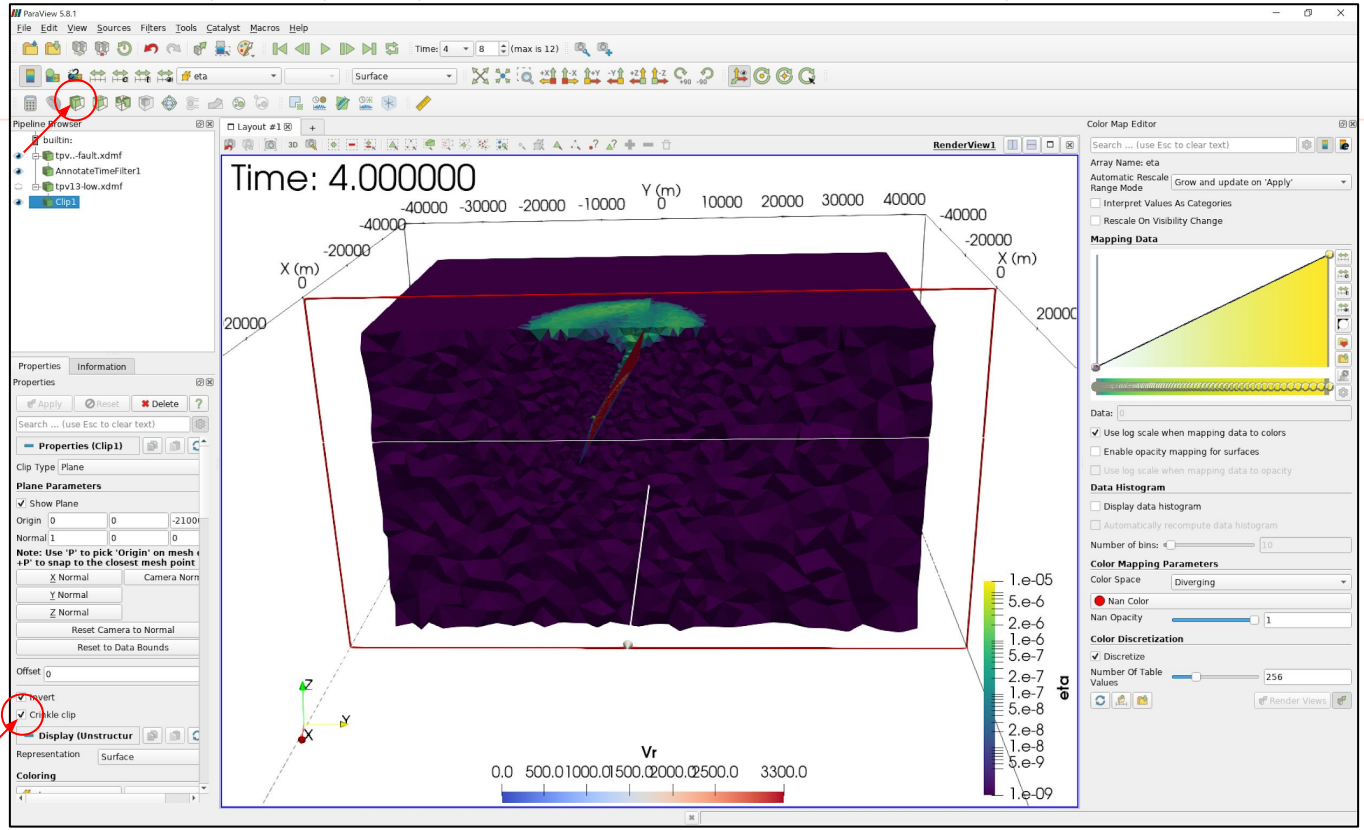
local desktop/laptop, Paraview: change colormap



local desktop/laptop, Paraview: model clip

select clip

crinkle clip



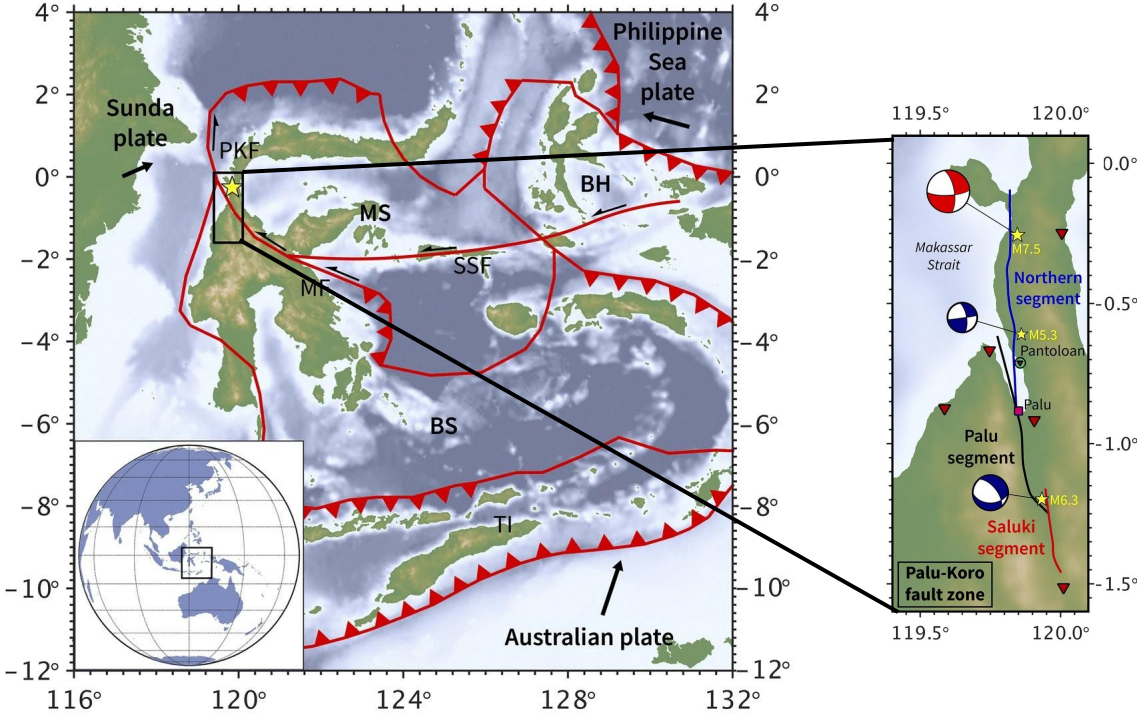
Done ! 😊

Let's go back to the main Zoom room

Example 3
The Palu Sulawesi earthquake

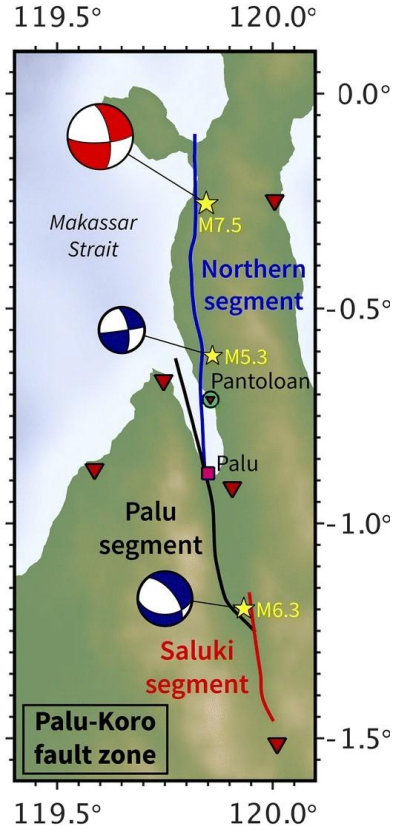
2018 Mw7.5 Palu, Sulawesi earthquake

- tectonic loading
- strike-slip fault system
- shallow depths
- followed by an unexpected localized tsunami within Palu Bay



Tectonic setting of the September 28, 2018 Mw 7.5 Sulawesi earthquake

Sulawesi earthquake - fault system

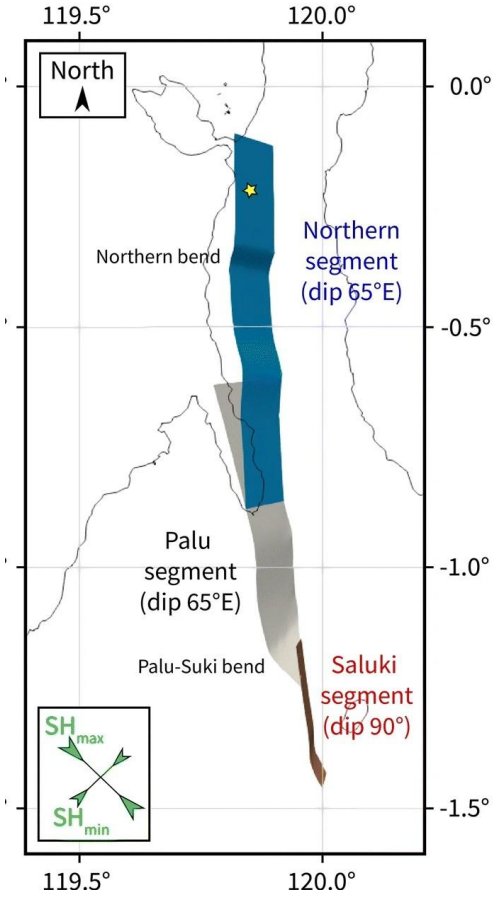


- the later two events provide constraints on the dip angles of individual segments of the fault network
- a complex 3D fault system can be created

left: Focal mechanisms and epicenters of the September 28, 2018 Palu earthquake (USGS (2018a), top), October 1, 2018 Palu aftershock (middle), and January 23, 2005 Sulawesi earthquake (bottom)

right: 3D model of the fault network viewed from top

(Ulrich et al., 2019)



Parameters setup

- A parameter file: **parameters.par**
- Several dependent files: **yaml :**

*__fault.yaml__ contains fault parameters

*__initial_stess.yaml__ contains initial stresses in 3D

*__material_3d.yaml__ assigns the initial stresses and lamé parameters

*__nucleation_stress.yaml__ forced nucleation within predefined patch

parameters.par

```
&equations
MaterialFileName = 'Sulawesi_material3d.yaml'
!off-fault plasticity parameter (ignored in Plasticity=0)
Plasticity=1
Tv=0.05
!Attenuation parameters (ignored if not compiled with attenuation)
FreqCentral=2.5
FreqRatio=100
/
&IniCondition
/
&Boundaries
BC_fs = 1                    ! enable free surface boundaries
BC_dr = 1                    ! enable fault boundaries
BC_of = 1                    ! enable absorbing boundaries
/
```

parameters.par

```
&DynamicRupture
FL = 103                    ! Friction law rate and state friction with strong
velocity weakening
!yaml file defining spatial dependance of fault properties
ModelFileName = 'Sulawesi_fault.yaml'

!non spatially dependent fault parameters
RS_f0 = 0.6
RS_sr0 = 1d-6
RS_b = 0.014
Mu_W=0.1
RS_iniSlipRate1 = 1d-16
RS_iniSlipRate2 = 0d0
t_0 = 0.5
```

parameters.par

```
!reference vector for defining strike and dip direction
XRef = -0.1                          ! Reference point
YRef = 0.0
ZRef = -1.0
refPointMethod = 1

RF_output_on = 0                     ! Rupture front ascii output
magnitude_output_on =0               ! Moment magnitude output
energy_rate_output_on =1             ! Moment rate output
OutputPointType = 5                  ! Type (5: ascii file and paraview file)
/
```

parameters.par

```
!see: https://seissol.readthedocs.io/en/latest/fault-output.html
! parameterize paraview file output
&Elementwise
printIntervalCriterion = 2                ! 1=iteration, 2=time
printtimeinterval_sec = 0.5               ! time interval at which output will be written
OutputMask = 1 1 1 1 1 1 1 1 1 1 1        ! turn on and off fault outputs
refinement_strategy = 2
refinement = 1
/

! parameterize ascii fault file outputs
&Pickpoint
printtimeinterval = 1                     ! Index of printed info at timesteps
OutputMask = 1 1 1 1 1 1 1 1 1 1 1        ! turn on and off fault outputs
nOutpoints = 1
PPFileName = 'faultreceiver_hypocenter.dat'
/
```

parameters.par

```
&MeshNml
MeshFile = 'Sulawesi_65dip_straightBay_ShortNorth_micro'
meshgenerator = 'PUML'                    ! Name of meshgenerator (PUML)
/

&Discretization
CFL = 0.5                                 ! CFL number (<=1.0)
FixTimeStep = 5                           ! Manually chosen minimum time
ClusteredLTS = 2                          ! 2: Local time stepping
!ClusteredLTS defines the multi-rate for the time steps of the clusters 2 for Local
time stepping
/
```

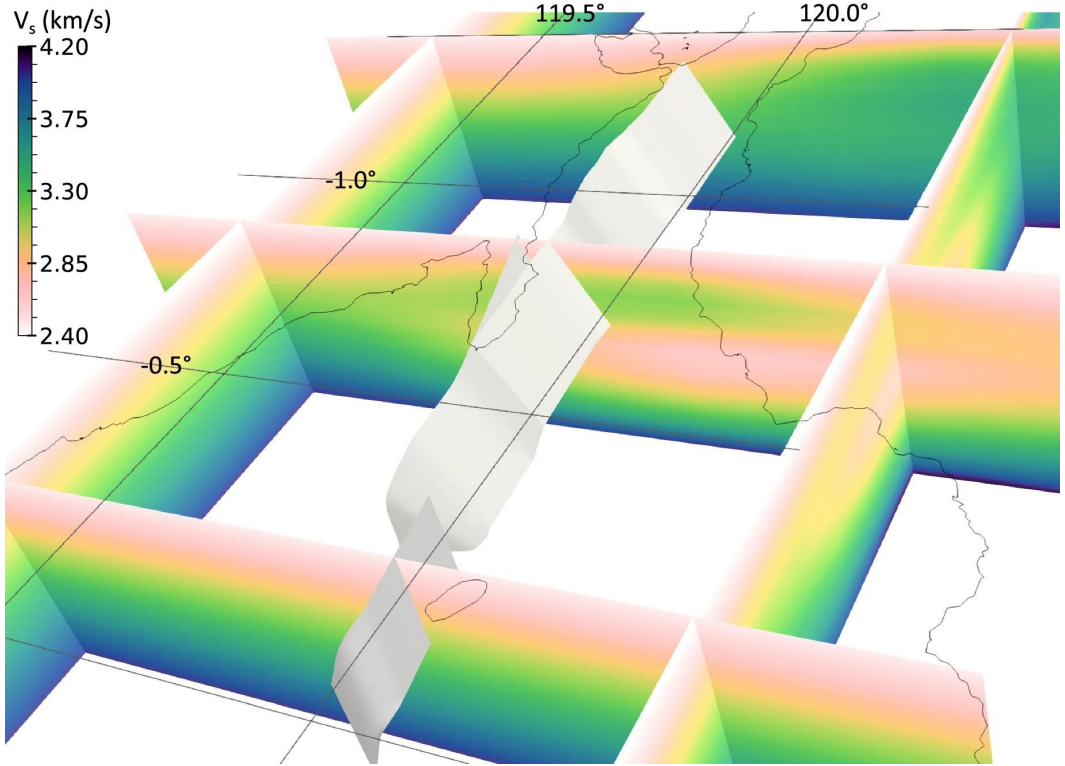
parameters.par

```
FaultOutputFlag = 1                    ! Dynamic Rupture output (add this line
only if active)
OutputFile = 'output/Sulawesi'
Format = 10                            ! Format (10= no output, 6=hdf5 output)

!          |stress     |vel  |plastic strain output (if any)
iOutputMask = 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1
printIntervalCriterion = 2             ! Criteria for index of printed info (2=time)
TimeInterval = 5.                      ! Index of printed info at time
refinement = 2
```

parameters.par

```
! off-fault ascii receivers
nRecordPoints = 33                          ! number of Record points which are read from file
RFileName = 'GPSfiltered_proj_200m_8e6.dat'    ! Record Points in extra file
pickdt = 0.01                               ! Pickpoint Sampling
pickDtType = 1                              ! Pickpoint Type
! (Optional) Synchronization point for receivers.
!If omitted, receivers are written at the end of the simulation.
ReceiverOutputInterval = 1.0

! Free surface output
SurfaceOutput = 1
SurfaceOutputRefinement = 1
SurfaceOutputInterval = 0.25
!ReceiverOutputInterval = 0.05

xdmfWriterBackend = 'posix' ! (optional)
```

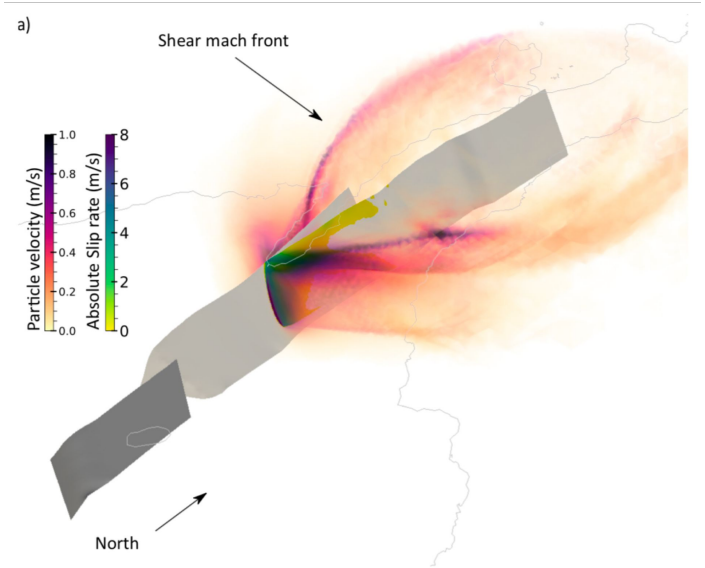
Sulawesi earthquake - 3D material properties



S-wave speeds (Vs) on five cross-sections of the 3D subsurface structure of Awaliah et al. (2018), incorporated into the model

(Ulrich et al., 2019)

Hand's on!


a)
Shear mach front
Particle velocity (m/s)
1.0
0.8
0.6
0.4
0.2
0.0
Absolute Slip rate (m/s)
8
6
4
2
0
North

training cluster:
run SeisSol

$ **cd Sulawesi**

(before submit job, please check if DGPATH, parameter files, mesh file, etc, exists in current folder !)

$ **qsub submit.sh**

To check job status:

$ **qstat**

desktop/laptop: post-processing

- Copy output files from remote (HLRS) to local (desktop/laptop)
- In your terminal:

```
$ scp -r scaXXXXX@training.hlrs.de:work/Sulawesi .
```

- We will use Paraview to visualize the surface and fault output
- Back up output link: `/shared/cheese/seissol/output/Sulawesi/`

SeisSol 2 go

You can use the Docker image to continue experimenting at home with SeisSol:

$ docker pull uphoffc/seissol-training

Northridge:

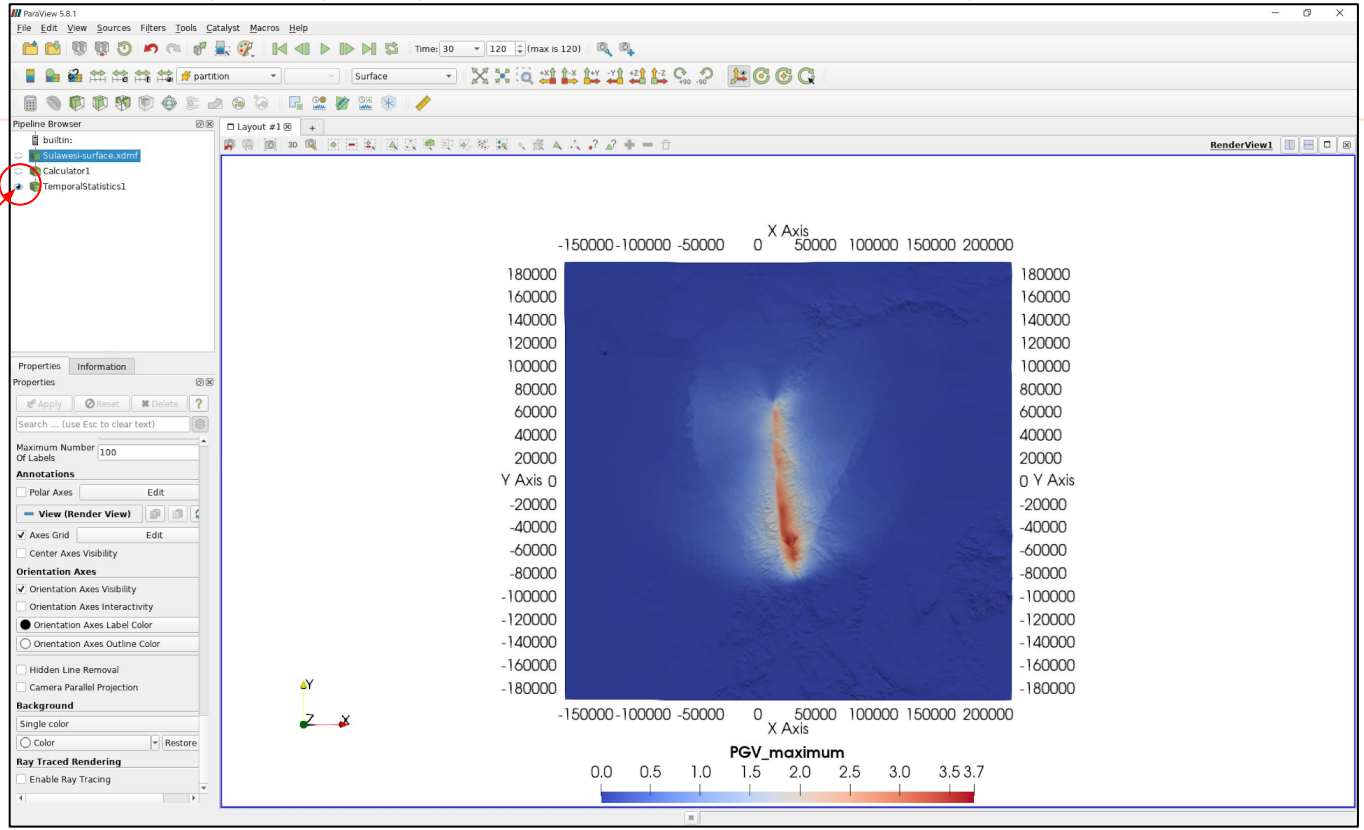
$ ./training.sh seissol parameters.par

TPV13 / Sulawesi:

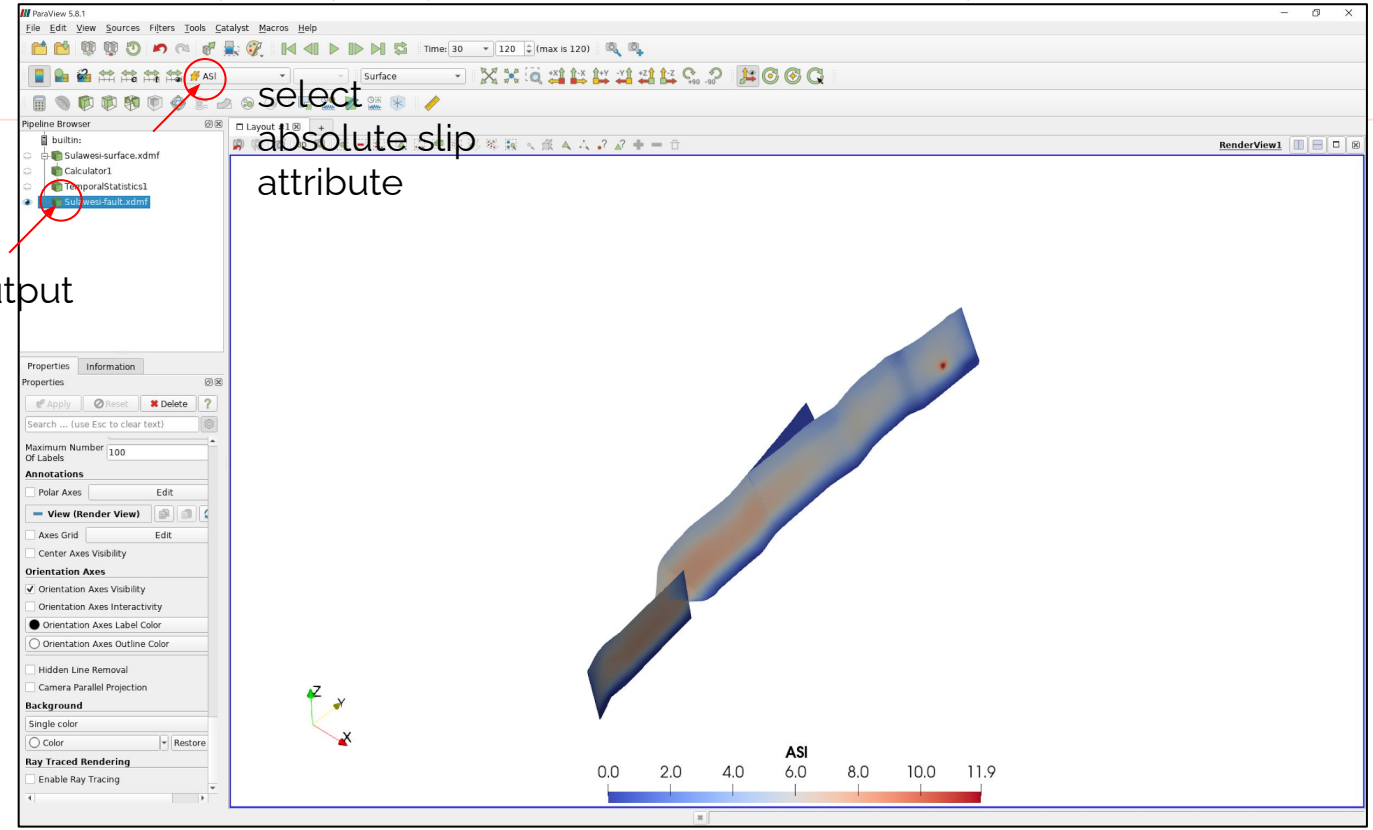
$./training.sh seissol_plasticity parameters.par

local desktop/laptop, Paraview: PGV map

follow previous exercise to generate PGV map



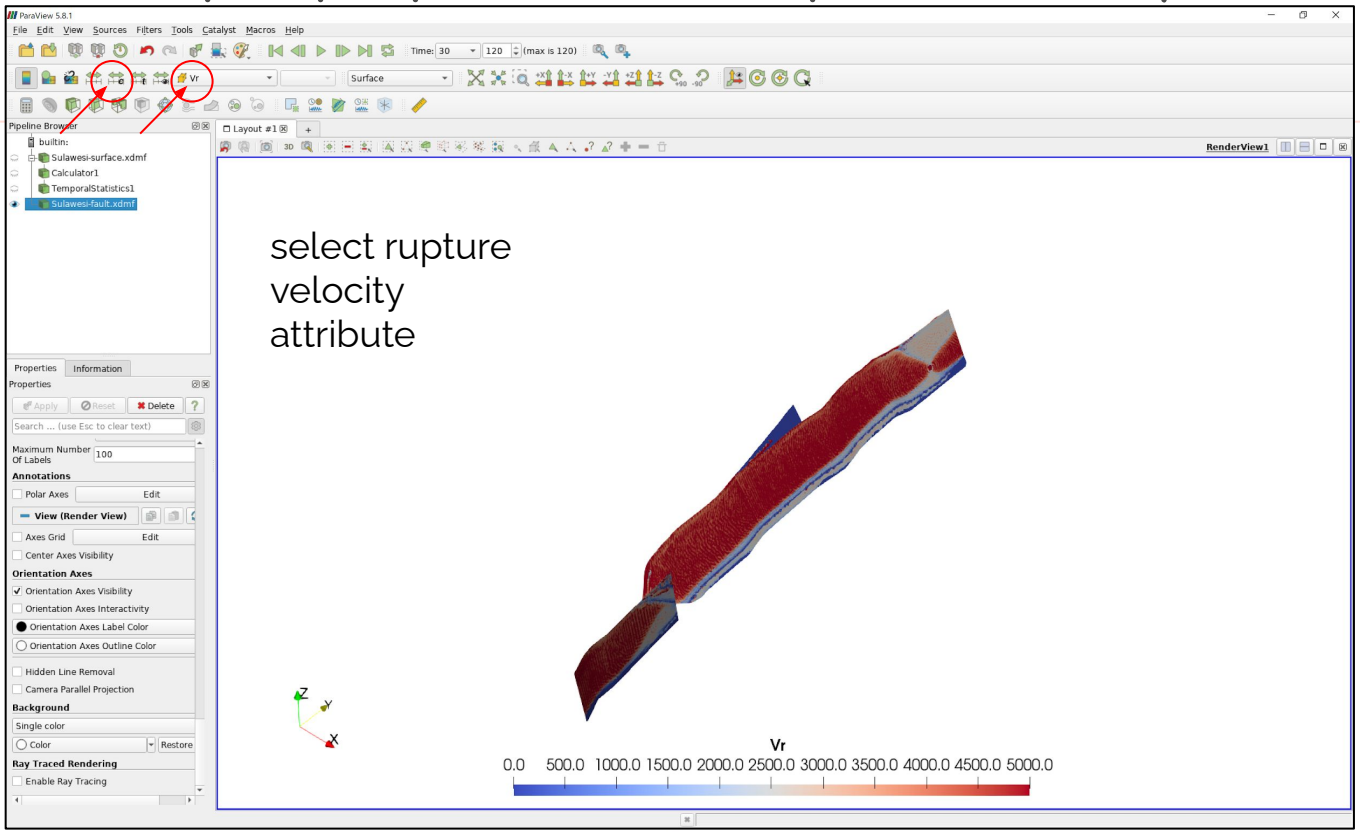
local desktop/laptop, Paraview: fault slip



load
fault output

local desktop/laptop, Paraview: rupture velocity

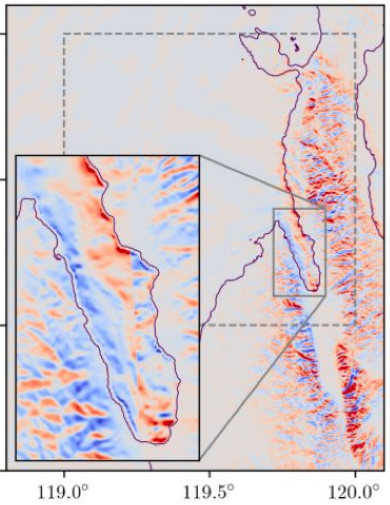
manually rescale data to range 0-5000 m/s

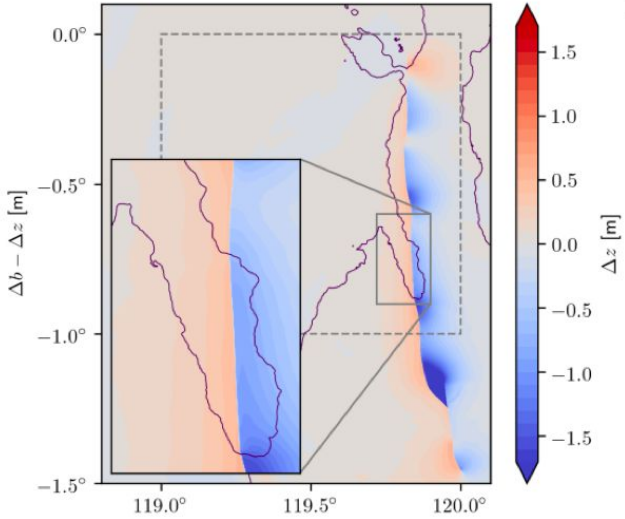


Rapid earthquake/tsunami modeling - The 2018, Palu-Sulawesi Event

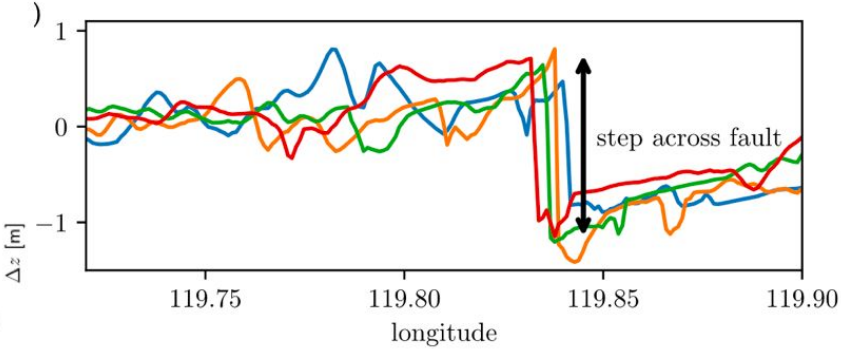
Ulrich et al., PAGEOPH 2019

Vertical displacements + Contribution of horizontal displacements Tanioka and Satake (1996)





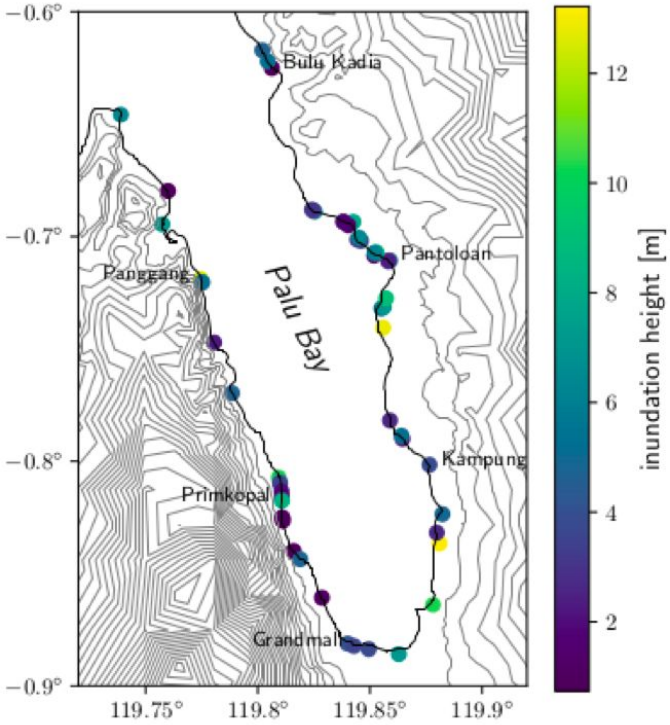
Step of ~1.5m across fault due to normal faulting component and horizontal movements beneath bathtub-like bathymetry



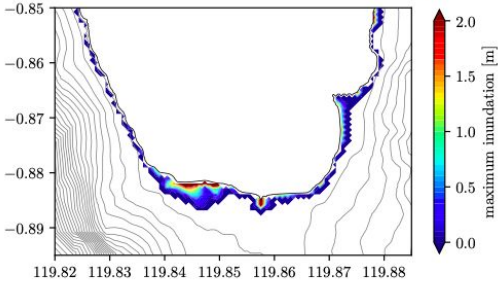
Modelled spontaneous coseismic oblique-slip on a dipping strike-slip fault is sufficient to produce reasonable tsunami amplitude and wave run-up.

Rapid earthquake/tsunami modeling - The 2018, Palu-Sulawesi Event

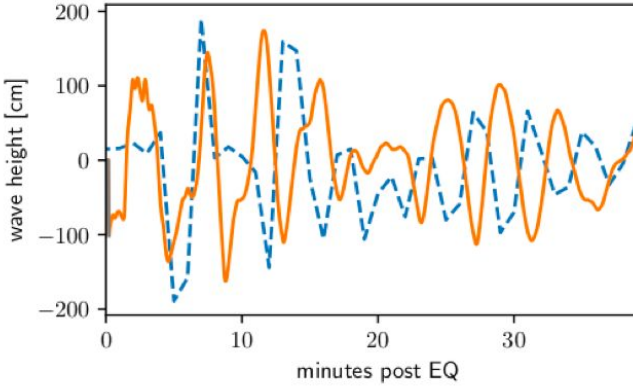
Ulrich et al., PAGEOPH 2019



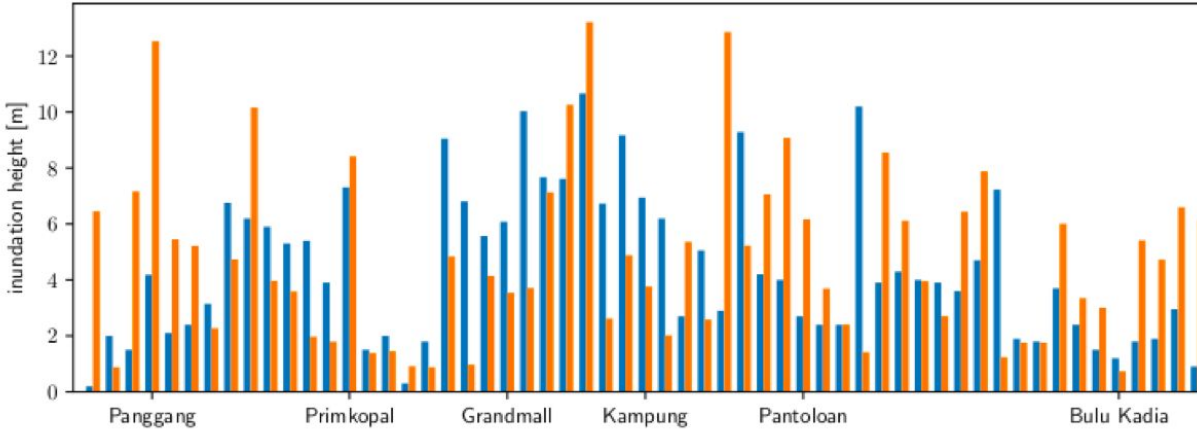
Model maximum inundation map



Model results compared with data at Pantaloan wave gauge



synthetics, observation



https://seissol.readthedocs.io/en/latest/index.html

SeisSol

latest

Search docs

INTRODUCTION

History

Compilation

A first example

Acknowledgements

Related publications

STRUCTURAL MODELS

CAD models

Meshing with SimModeler

Meshing with PUMGen

Gmsh

Docs » SeisSol

Edit on GitHub

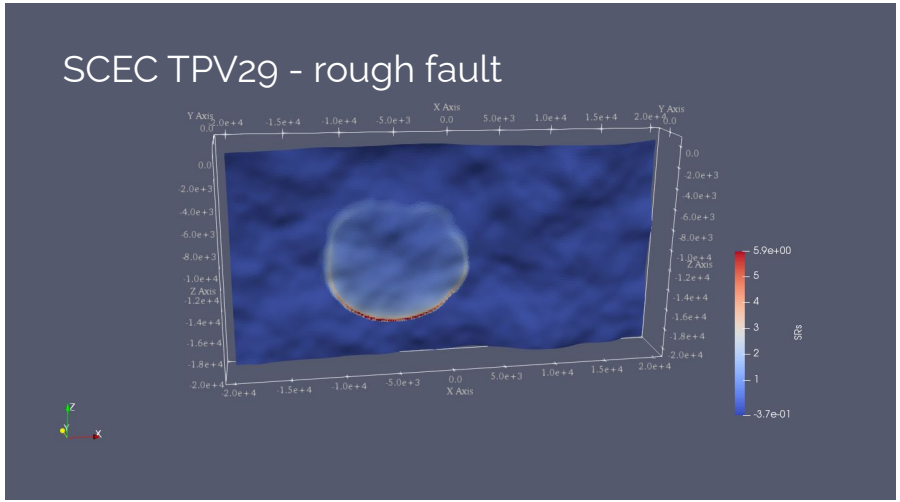
SeisSol

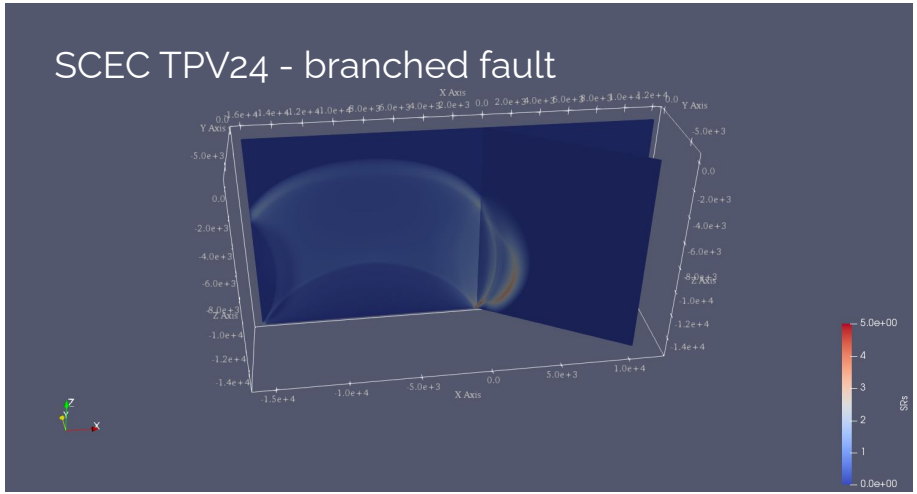
SeisSol is a software package for simulating wave propagation and dynamic rupture based on the arbitrary high-order accurate derivative discontinuous Galerkin method (ADER-DG).

Characteristics of the SeisSol simulation software are:

- use of arbitrarily high approximation order in time and space
- use of tetrahedral meshes to approximate complex 3D model geometries (faults & topography) and rapid model generation
- use of elastic, viscoelastic and viscoplastic material to approximate realistic geological subsurface properties
- parallel geo-information input (ASAGI)
- to produce reliable and sufficiently accurate synthetic seismograms or other seismological data set

SeisSol further examples, references and available reproducible models





more examples at SeisSol documentation
<https://seissol.readthedocs.io/en/latest/cookbook_overview.html>

SeisSol further examples, references and available reproducible models

Palgunadi, Kadek Hendrawan, Alice-Agnes Gabriel, Thomas Ulrich, José Ángel Lopéz-Comino, and Paul Martin Mai (2020), Dynamic Fault Interaction during a Fluid-Injection-Induced Earthquake: The 2017 Mw 5.5 Pohang Event, BSSA, doi:10.1785/0120200106, open access version available at https://eartharxiv.org/w5b9s/.

Ulrich, Thomas, Alice-Agnes Gabriel, Jean-Paul Ampuero, and Wenbin Xu (2019), Dynamic viability of the 2016 Mw 7.8 Kaikōura earthquake cascade on weak crustal faults, Nature Communications, 10(1213), doi:10.1038/s41467-019-09125-w.

Ulrich, Thomas, Stefan Vater, Elizabeth H. Madden, Joern Behrens, Ylona van Dinther, Iris van Zelst, Eric J. Fielding, Cunren Liang, and Alice-Agnes Gabriel (2019), Coupled, Physics-based Modelling Reveals Earthquake Displacements are Critical to the 2018 Palu, Sulawesi Tsunami, Pure and Applied Geophysics

Wollherr, Stephanie, Alice-Agnes Gabriel, and Paul Martin Mai (2019), Landers 1992 ”reloaded”: an integrative dynamic earthquake rupture model, Journal of Geophysical Research - Solid Earth, 124, doi:10.1029/2018JB016355,

Wollherr, Stephanie, Alice-Agnes Gabriel, and Carsten Uphoff (2018), Off-fault plasticity in three-dimensional dynamic rupture simulations using a modal Discontinuous Galerkin method on unstructured meshes: Implementation, verification, and application, Geoph.J.Int., 214(3), 1556–1584, doi:10.1093/gji/ggy213.

Uphoff, Carsten, Sebastian Rettenberger, Michael Bader, Elizabeth H. Madden, Thomas Ulrich, Stephanie Wollherr, and Alice-Agnes Gabriel (2017), Extreme Scale Multi-Physics Simulations of the Tsunamigenic 2004 Sumatra Megathrust Earthquake, Proceedings of the International Conference for High Performance Computing, Networking, Storage and Analysis SC17, doi:10.1145/3126908.3126948.

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Heinecke, A., et al. (2014), Petascale High Order Dynamic Rupture Earthquake Simulations on Heterogeneous Supercomputers, in SC '14: Proceedings of the International Conference for High Performance Computing, Networking, Storage and Analysis, pp. 3-14, doi:10.1109/SC.2014.6, Gordon Bell Prize Finalist 2014.

SeisSol further examples, references and available reproducible models

Pelties, Christian, Alice-Agnes Gabriel, and Jean-Paul Ampuero (2014), Verification of an ADER-DG method for complex dynamic rupture problems, Geoscientific Model Development, 7(3), 847-866, doi:10.5194/gmd-7-847-2014.

Wenk, Stefan, Christian Pelties, Heiner Igel, and Martin Käser (2013), Regional wave propagation using the discontinuous Galerkin method, Solid Earth, 43-57, doi:10.5194/se-4-43-2013.

Pelties, Christian, Josep De la Puente, Jean-Paul Ampuero, Gilbert B. Brietzke, and Martin Käser (2012), Three-Dimensional Dynamic Rupture Simulation with a High-order Discontinuous Galerkin Method on Unstructured Tetrahedral Meshes, J. Geophys. Res. - Solid Earth, doi:10.1029/2011JB008857.

Chaljub, Emmanuel, Peter Moczo, Seiji Tsuno, Pierre-Yves Bard, Jozef Kristek, Martin Käser, Marco Stupazzini, and Miriam Kristekova (2010), Quantitative Comparison of Four Numerical Predictions of 3D Ground Motion in the Grenoble Valley, France,

Bull. Seis. Soc. Am., 100(4), 1427-1455, doi:10.1785/0120090052.

Käser, Martin, Hugues Djikpesse, and Michael Prange (2010), Numerical Modeling of Borehole-guided Waves and Reservoir Formation Reflections, in SEG Expanded Abstracts, vol. 29, pp. 573-577, doi:10.1190/1.3513849.

De la Puente, Josep, Michael Dumbser, Martin Käser, and Heiner Igel (2008), Discontinuous Galerkin Methods for Wave Propagation in Poroelastic Media, Geophysics, 73(5), T77-T97, doi:10.1190/1.2965027.

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SeisSol further examples, references and available reproducible models

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January 11, 2019 — Dataset — Open Access

SeisSol model setup of the Kaikōura's dynamic rupture model of Ulrich et al.

Ulrich, Thomas; Gabriel, Alice-Agnes; Ampuero, Jean-Paul; Xu, Wenbin

All data required to run the dynamic rupture model of the Kaikōura earthquake presented in Ulrich, T., Gabriel, A. A., Ampuero, J. P., & Xu, W. (2018). Dynamic viability of the 2016 Mw 7.8 Kaikōura earthquake cascade on weak crustal faults. A detailed readme file summarizing the data and data formats is also provided.

Files (2.8 GB)

Name	Size	
NZ_asagi.nc md5:5b99f8d6191923e12c04826d0fd2a55f	75.7 MB	Download
NZ_asagi_att.nc md5:1ecc27c8174b8eba0c97eaf234828fce	50.5 MB	Download
NZ_fault.yaml md5:8ee52ea5327e7fb47cebb4f0d82c6ed9	1.1 kB	Download
NZ_initial_stress.yaml md5:9c79f0e6fd37ae7562ed308da23a184a	3.8 kB	Download
NZ_material.yaml md5:1b7fb0c8dc4d9c064ceff49d951cf2e2	860 Bytes	Download
NZ_nucleation_stress.yaml md5:59df05e8cbbf8cbd08ac7c3d8440ed62	1.2 kB	Download

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May 29, 2019 — Dataset — Open Access

SeisSol dynamic rupture model setup of the Mw 7.5 Palu earthquake scenario published in Ulrich et al. (2019)

Thomas Ulrich; Stefan Vater; Elizabeth H. Madden; Joern Behrens; Ylona van Dinther; Iris van Zelst; Eric J. Fielding; Cunren Liang; Alice-Agnes Gabriel

All data required to run the dynamic rupture model of the Palu earthquake presented in:

Ulrich, T., Vater, S., Madden, E. H., Behrens, J., van Dinther, Y., van Zelst, I., Fielding, E. J., Liang, C. & Gabriel, A. A. (2019). Coupled, Physics-based Modeling Reveals Earthquake Displacements are Critical to the 2018 Palu, Sulawesi Tsunami. doi: 10.31223/osf.io/3bwqa.

A detailed readme file summarizing the data and data formats is also provided.

Files (341.8 MB)

Name	Size	
3dvel_Sulawesi.nc md5:f6c1b69b8695eb8b8f9791ba52958ae6	1.2 MB	Download
3dvel_Sulawesi_BMKG.nc md5:431ed396ebf3d4717dfb324ad13d6ab2	219.0 kB	Download
faultreceiver_hypocenter.dat md5:15cb10af1a45f365939b2a80c19c7f43	41 Bytes	Download
GPSfiltered_proj_200m_8e6.dat md5:28419db0f5550f0802d711ba5209fdd0	1.7 kB	Download
parameters.par	4.1 kB	Download

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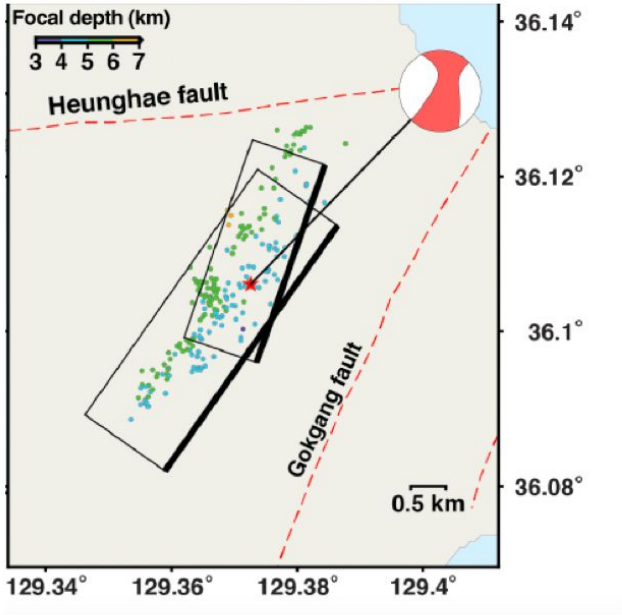
The 2017, Pohang induced earthquake

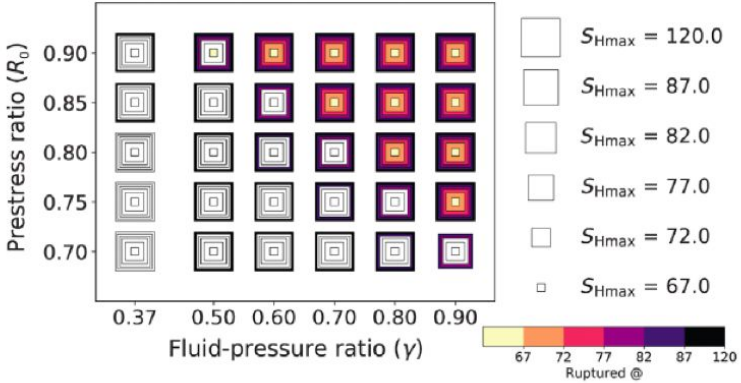
Dynamic Fault Interaction during a Fluid-Injection-Induced Earthquake: The 2017 M_w 5.5 Pohang Event

Kadek Hendrawan Palgunadi*[1], Alice-Agnes Gabriel[2], Thomas Ulrich[2], José Ángel López-Comino[1,3,4,5], and Paul Martin Mai[1]



Ensemble simulations constrain competing views

- Static failure analysis and 180 numerical simulations demonstrate that the **regional loading stress is unable to generate dynamic rupture consistent with the observed faulting style**.
- **Overpressurized pore fluids, non-optimally oriented and dynamically weak faults, and a close to critical local stress** govern a data-constrained scenario
- Dynamic fault interaction of two slightly off-set fault planes (partially) reproduce observations of a **strong CLVD component.**



Add-on (if time allows) building a 3D model with complicated geometries using SimModeler

Geometry

We will build a 3D model with complicated geometries using **SimModeler**:

1. Creating a high resolution topography and bathymetry free surface and merge it with a simple box model

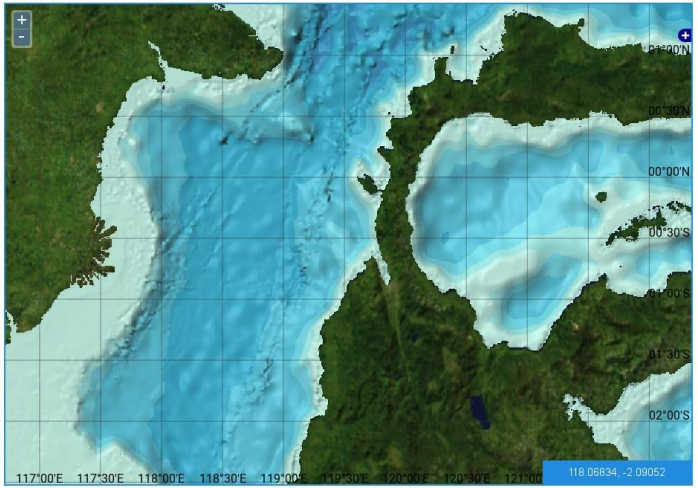
2. Creating complex fault networks constrained by fault traces and dip

3. Volume meshing with unstructured tetrahedral meshing

Creating the topographic layer

- We create the topography from a NetCDF file downloaded from GEBCO https://www.gebco.net/.

- We then project the data, triangulate it, and export it as stl (list of triangles):



Define your search box coordinates - input order is most westerly, southerly, easterly, northerly. Alternatively use keyboard **Shift**+mouse **Left Click** and **Drag** a box to define your area of interest on the above map

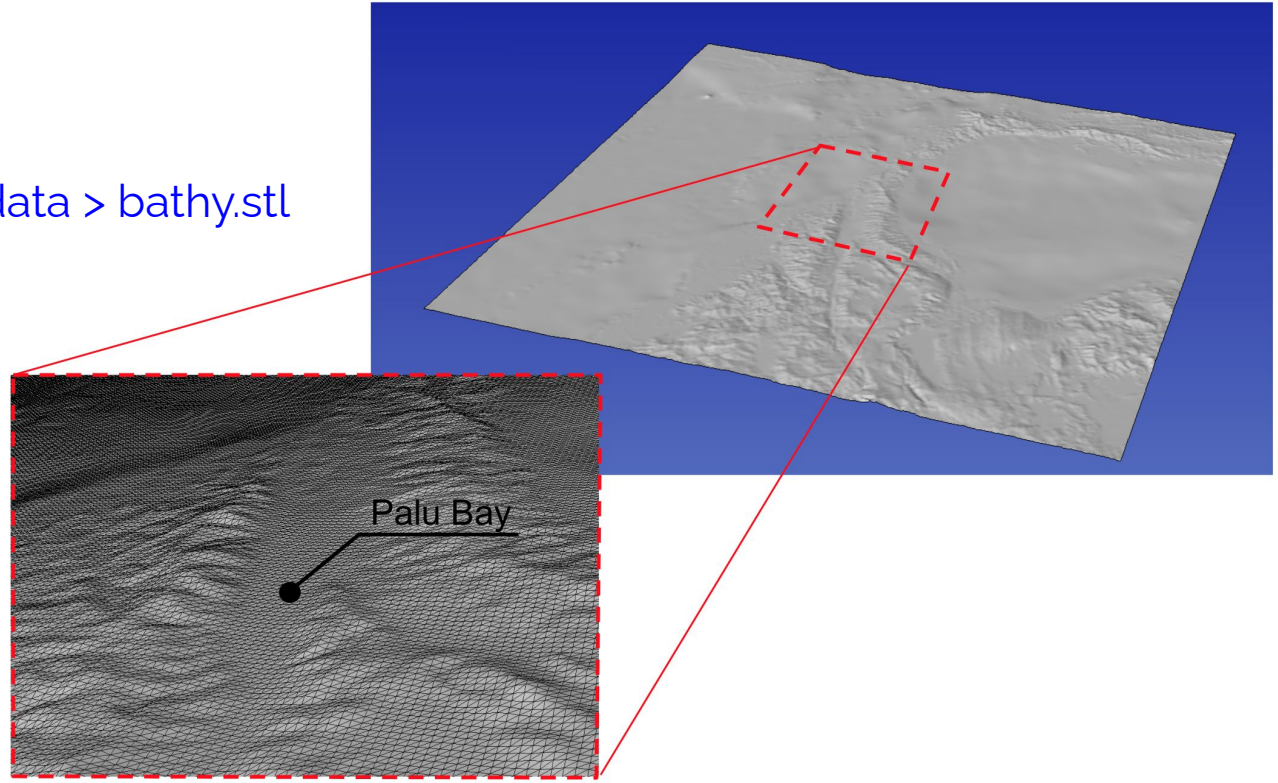
118, -3,121,2 Clear

Coordinates should be decimal degrees (maximum - 5 decimal places) where West and South are entered as negatives and East and North as positives. For example 20 W, 5 S, 10 W, 2 N = -20.0,-5.0,-10.0,2.0

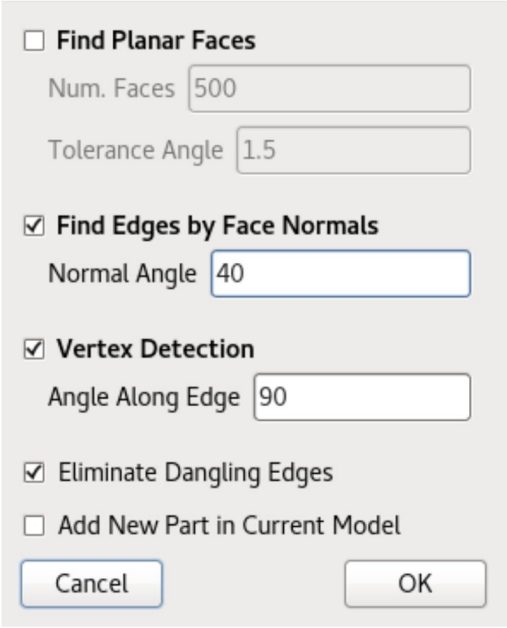
```
python createGOCADTSurfNXNY_netcdf.py --proj +init=EPSG:23839
data/GEBCO_2014_2D_118.1904_-2.4353_121.6855_1.0113.nc bathy.stl
```

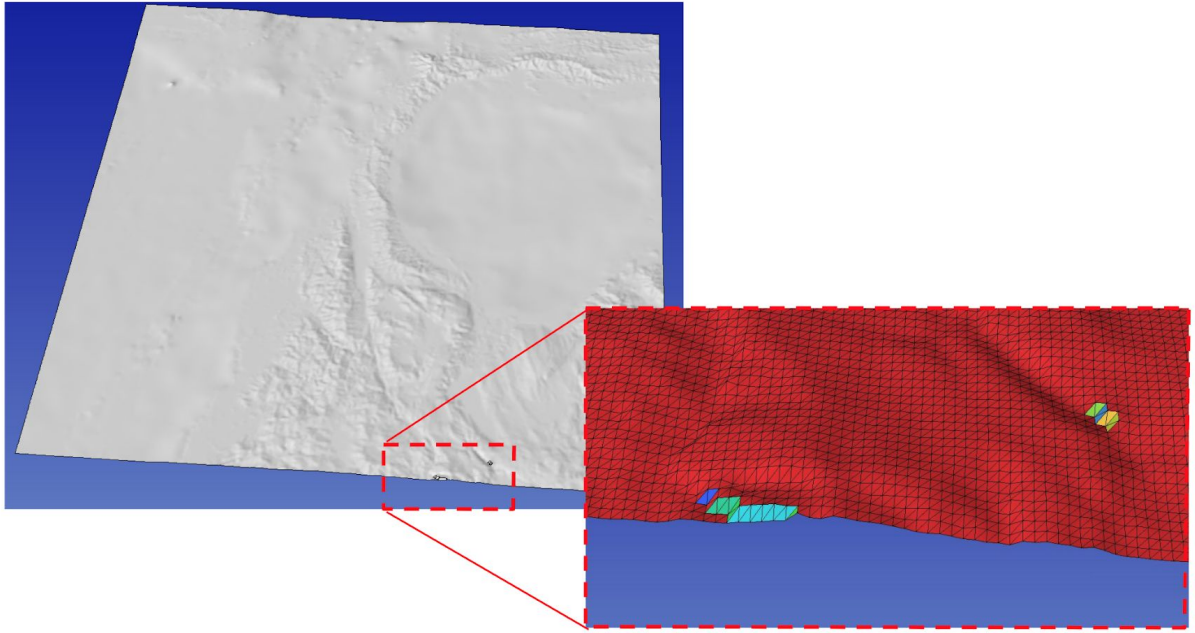
- We then load the stl file into **SimModeler**:

File > Import discrete data > bathy.stl



Note that in SimModeler import options, importing with a small angle isolate tiny faces from the main surface, that then needs to be accounted for by the mesh.





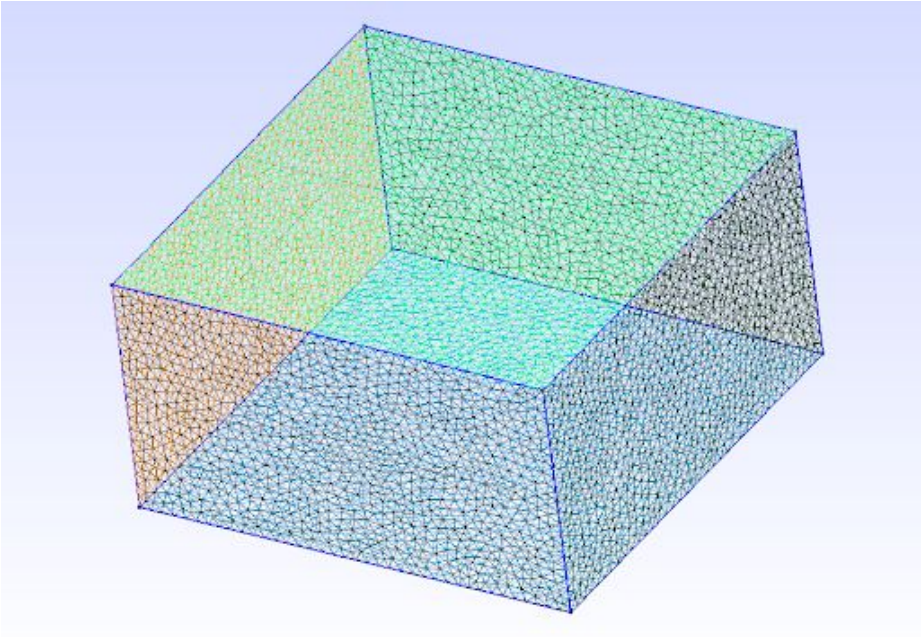
Creating the domain box

We generate a simple box with **Gmsh**:

```
gmsh -2 create_box.geo -format stl
```

The box dimensions are such as the topography is slightly wider than the box. The mesh size is chosen small enough to facilitate intersection with topography and large enough to limit the number of elements.

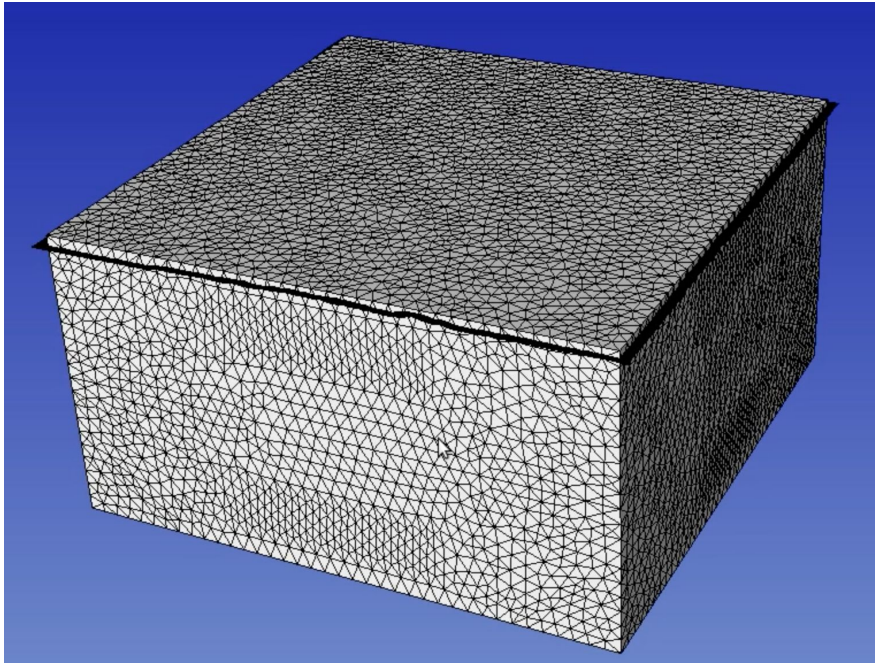
```
mesh_size = 10e3;
Xmax = -160e3; Xmin = 215e3;
Ymin = 1235e3; Ymax = 1605e3;
Zmin = -200e3; Zmax = 5e3;
```



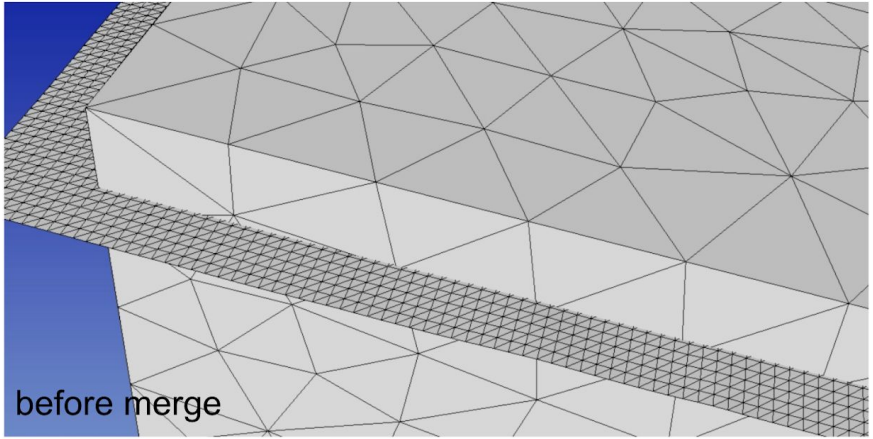
Merging topographic layer with box model

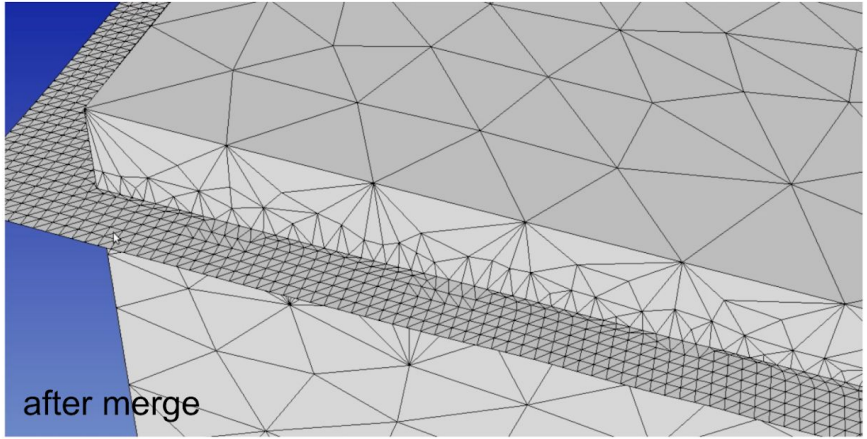
We first import `create_box.stl` with import options:

- activating **'Edges by Face Normals'** with normal angle 60◦,
- activating **'Vertex Detection'** with angle along edge 90◦, and
- eliminating **'Dangling Edges'.**
- Then we import the topographic layer bathy.stl with increasing **'Edges by Face Normals'** normal angle to 80◦, and
- activating **'Add New Part in Current Model'**.

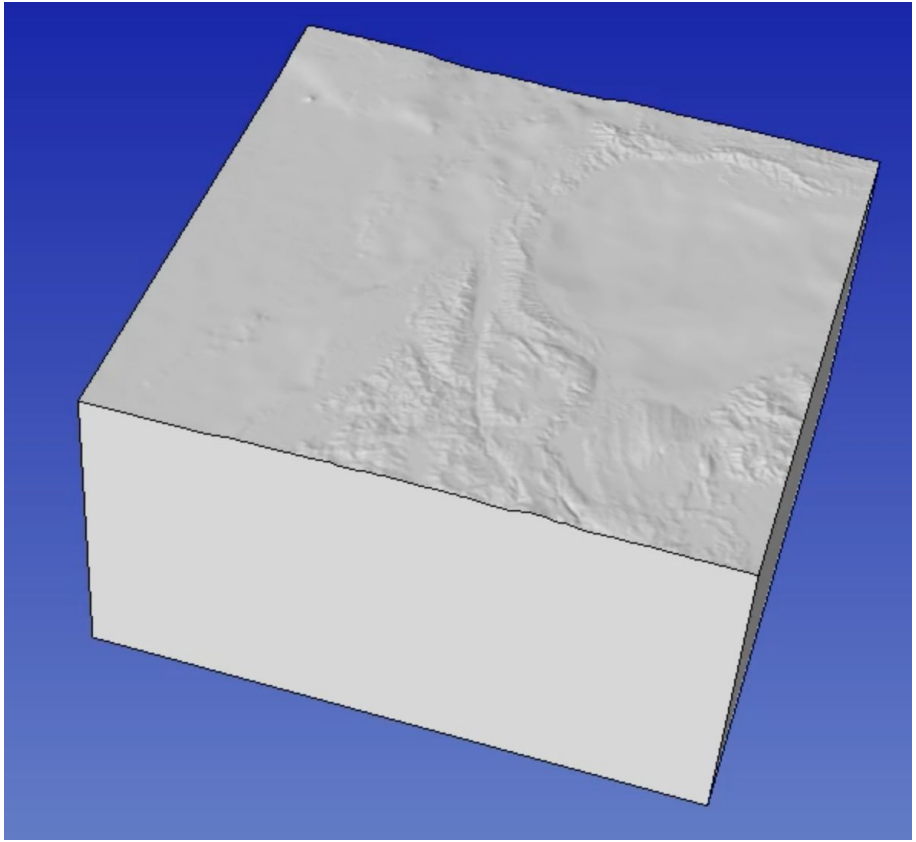


We then merge both models by using **'Union Parts'** in the **'Discrete'** tab and apply with tolerance 0.1.



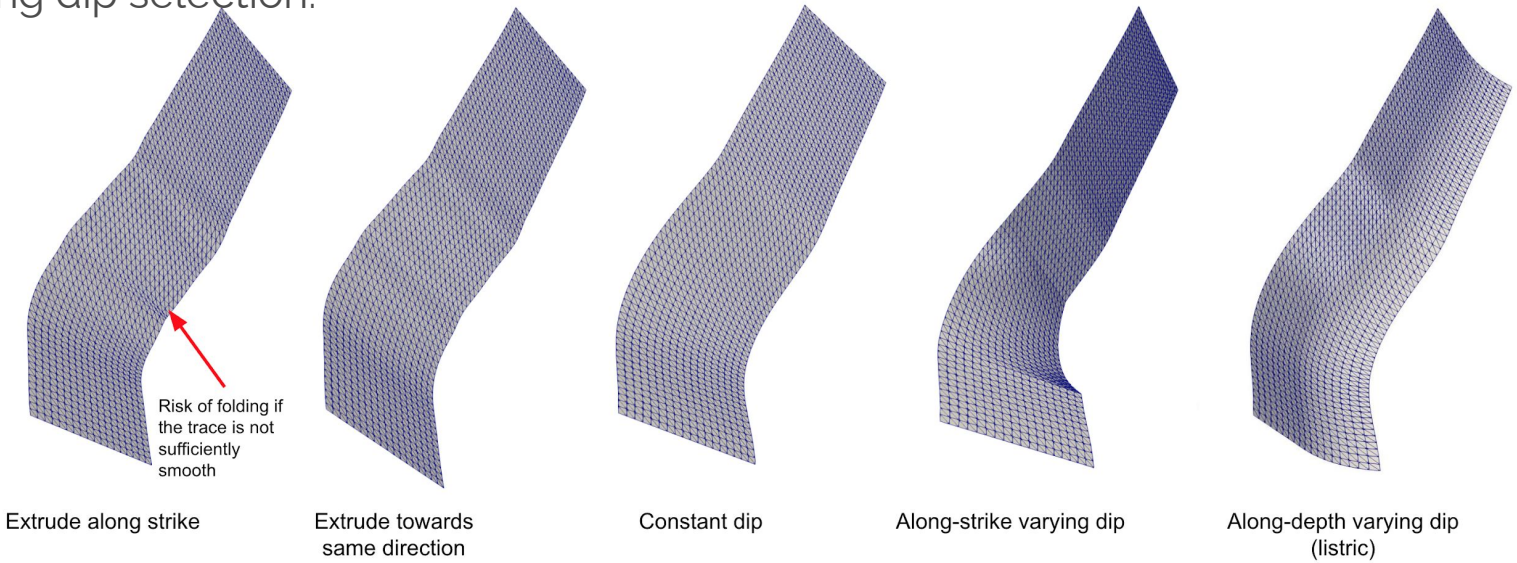


We then remove excess from both models using **‘Delete’** in the **‘Discrete’** tab.



Building faults from trace and dip

We generate the fault plane using `createFaultFromCurve.py`. Note that during building a fault model we need: smooth and resample fault trace, sweep trace towards z positive (because the topography can have positive z) and negative z, and constant or varying dip selection.



Application to Palu

The **'data'** folder contains (x,y,z) ASCII files describing fault traces and dip variation along-strike. The faults then are straightforwardly created using:

```
dx=0.5e3
python ~/SeisSol/Meshing/GocadRelatedScripts/createFaultFromCurve.py
data/segmentSouth_d90_long.dat 0 90 --dd $dx --maxdepth 16e3 --extend
4e3
python ~/SeisSol/Meshing/GocadRelatedScripts/createFaultFromCurve.py
data/smootherNorthBend.dat 0 65 --dd $dx --maxdepth 16e3 --extend 4e3
python ~/SeisSol/Meshing/GocadRelatedScripts/createFaultFromCurve.py
data/segmentBayAndConnectingFault.dat 2
data/segmentBayAndConnectingFaultDip.dat --dd $dx --maxdepth 16e3
--extend 4e3
```

Merging box and faults

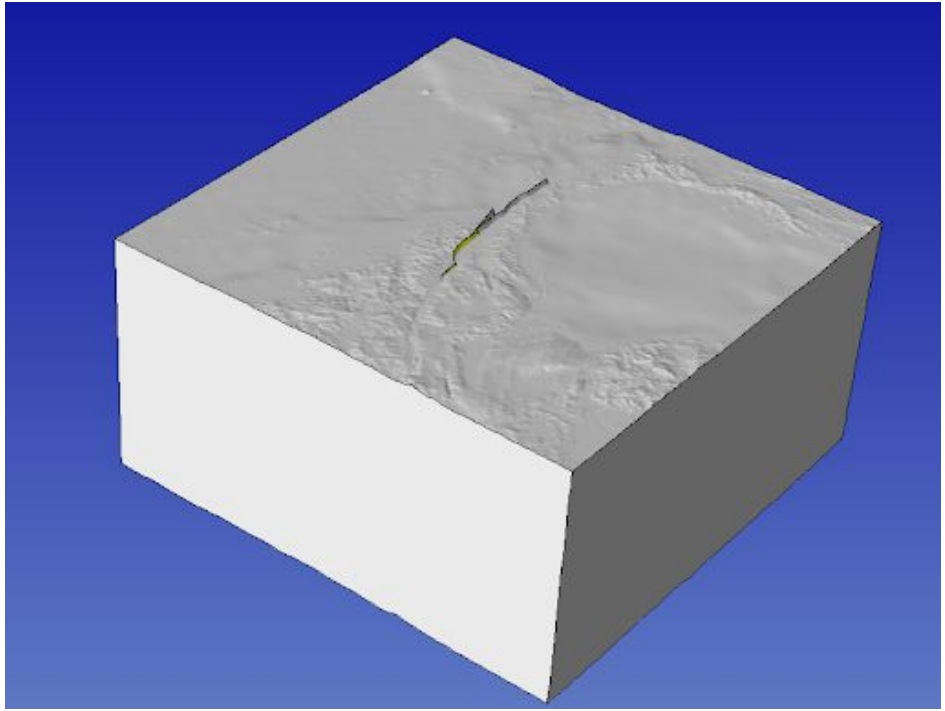
Let suppose that we know have 2 smd file, one with the intersected faults, the other with the box.

We can open one of them by:

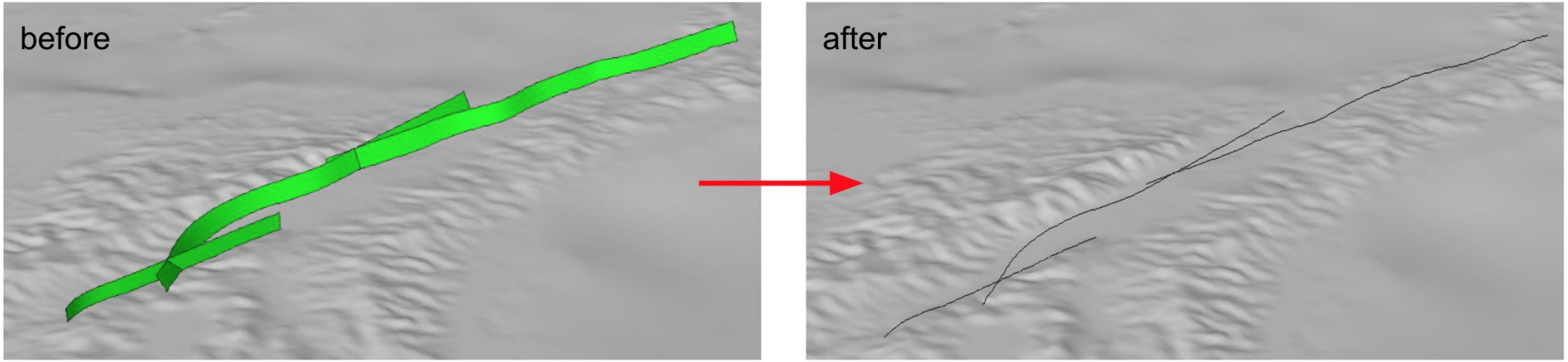
Discrete > Add parts > select the other.

Discrete > Union Parts > select both parts.

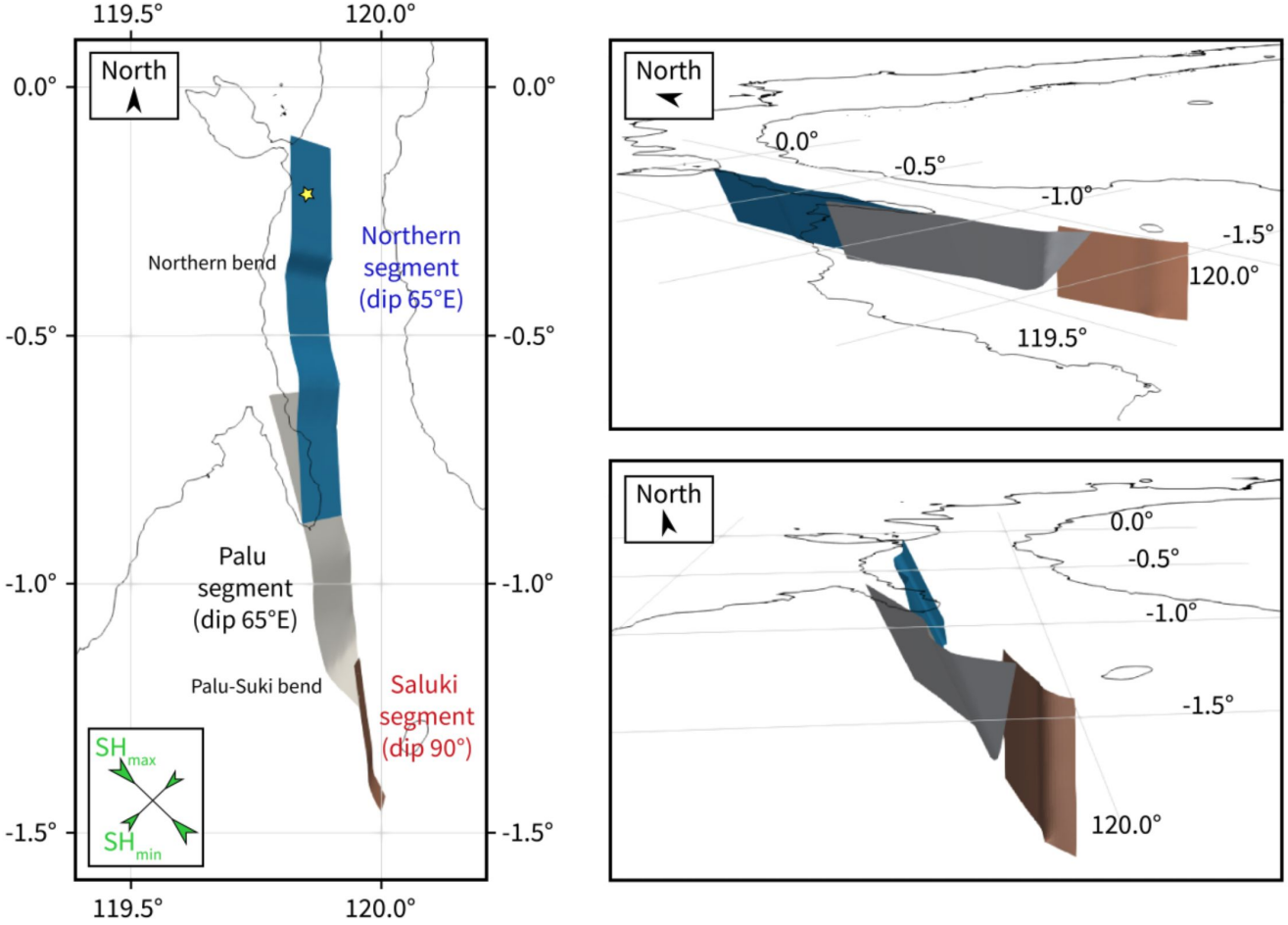
This intersects the faults with the topography.



Now we just have to delete the faults parts above the topography.

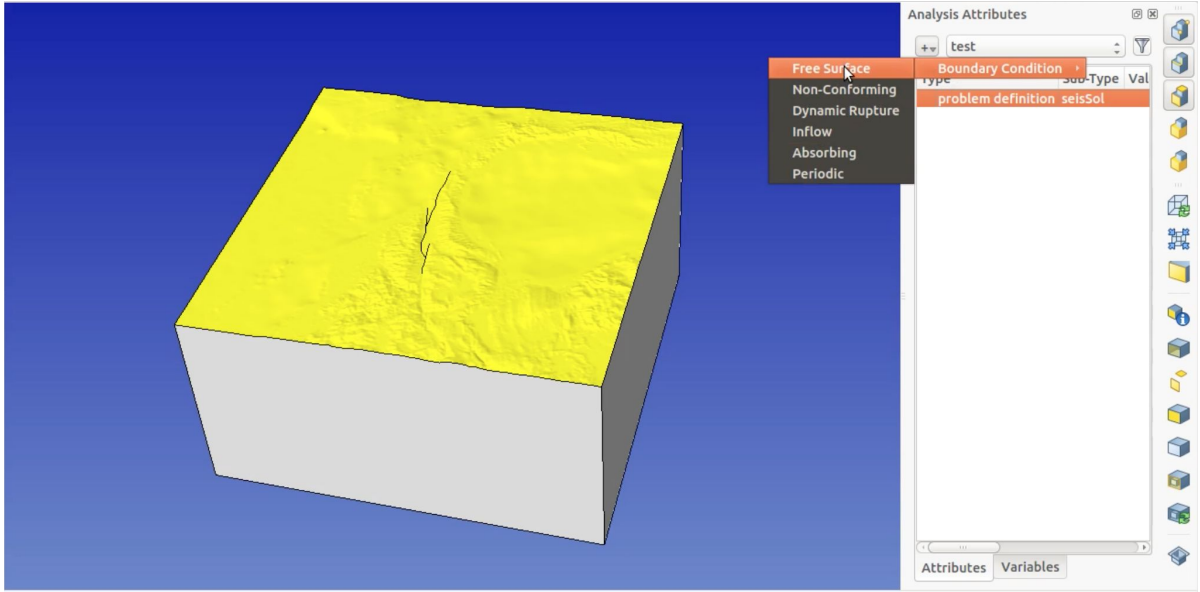


and the model is finished.

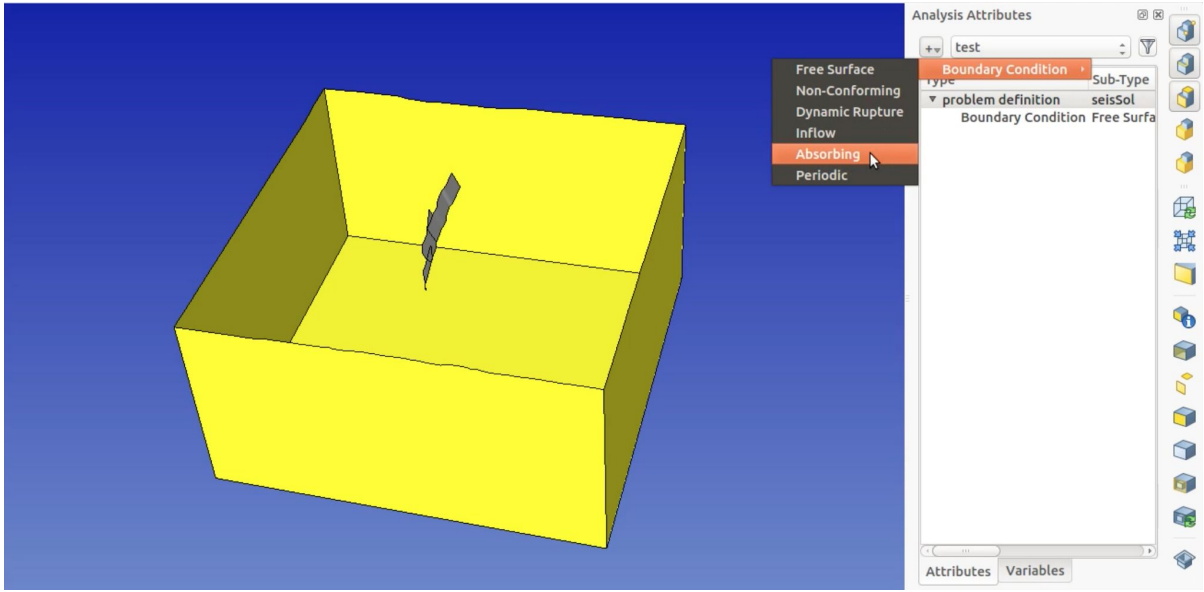

119.5°
120.0°
0.0°
-0.5°
-1.0°
-1.5°
North
Northern bend
Northern segment (dip 65°E)
Palu segment (dip 65°E)
Palu-Suki bend
Saluki segment (dip 90°)
SH max
SH min
North
0.0°
-0.5°
-1.0°
-1.5°
120.0°
119.5°
North
0.0°
-0.5°
-1.0°
-1.5°
120.0°

Assigning boundary conditions

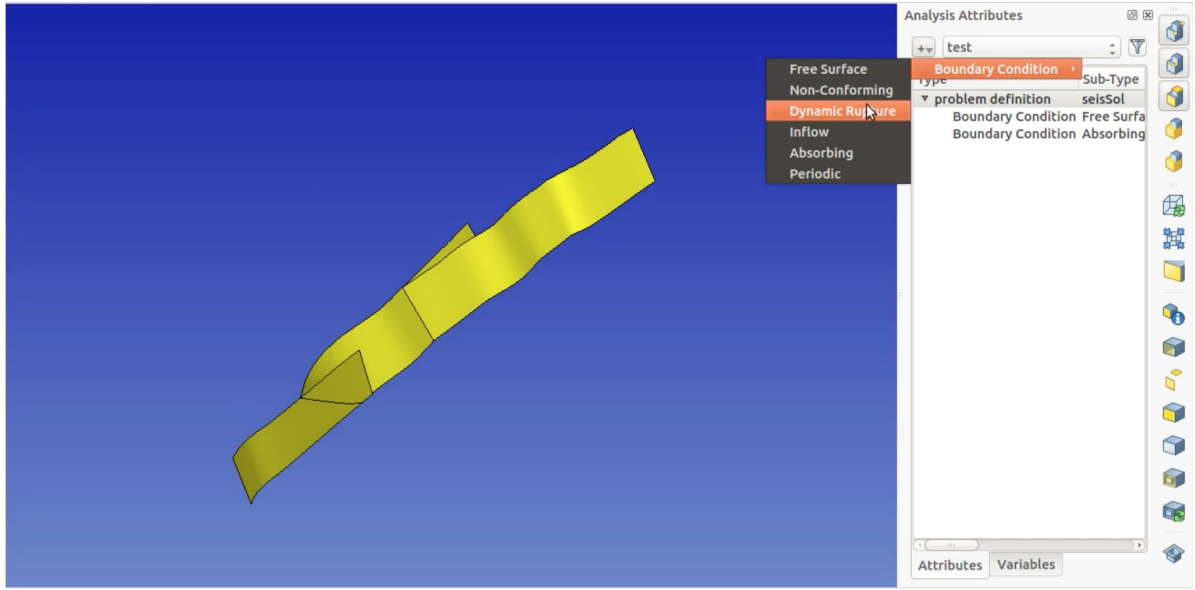
In SimModeler, select **'Analysis'** tab then select **'Analysis Attributes'.** We need to name a **'New Case …'** and select with **'SeisSol'** as the solver. Then select the top surface and assign it with **'Free Surface'** boundary condition.



We hide the top surface, then select all sides and bottom surfaces and assign them with **'Absorbing'** boundary condition.



We hide all sides and bottom surfaces, then select all fault segments and assign them with **‘Dynamic Rupture’** boundary condition.



Setting meshing parameters

We then Select **'Meshing'** tab and select **'Mesh Size'** to absolute 300 m within the fault segments.

Next we set **'Mesh Size'** to absolute 20000 m at the far side of our domain.

We also set **'Gradation Rate'** to 0.3.

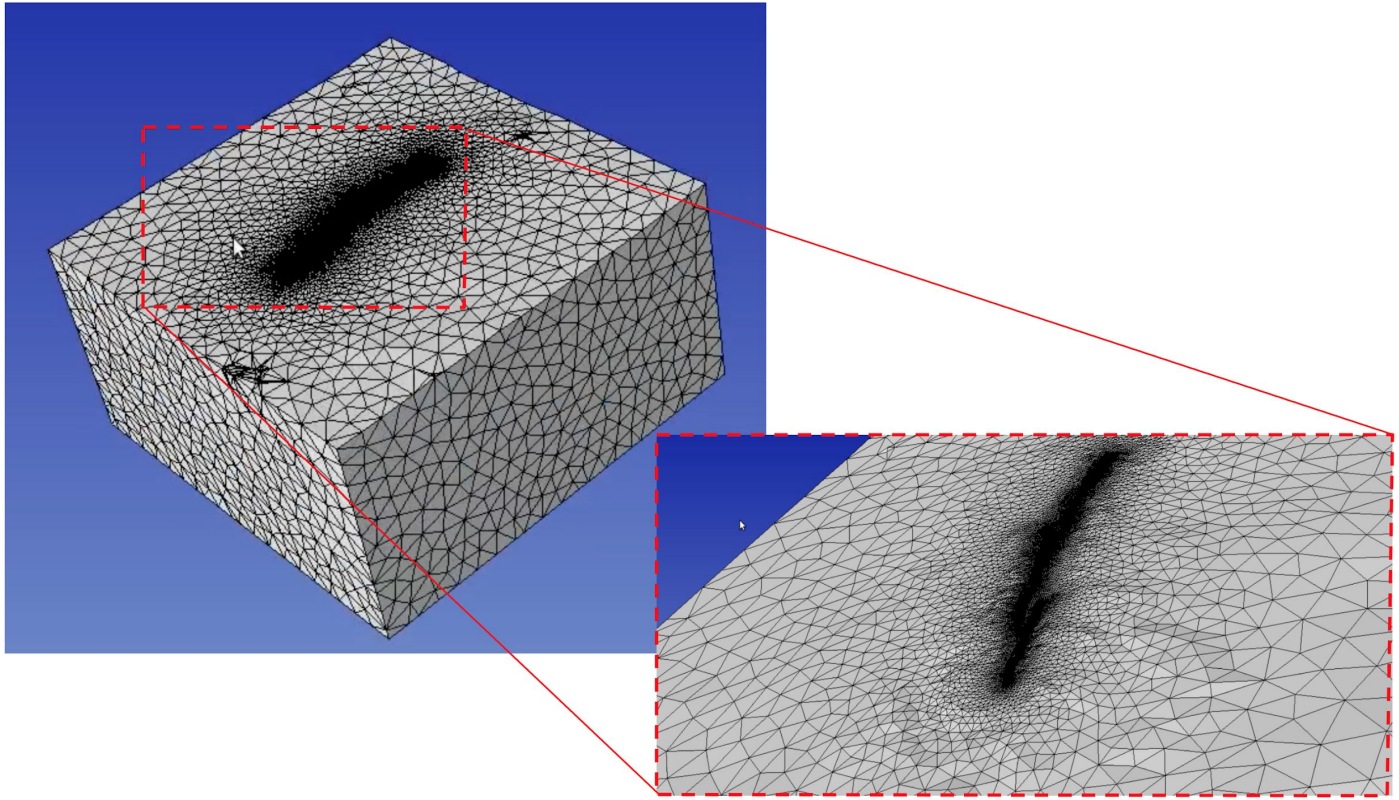
Then we set **'Surface Shape Metric'** with limiting aspect ratio to 6.0 and set **'Volume Shape Metric'** with limiting aspect ratio to 12.0.

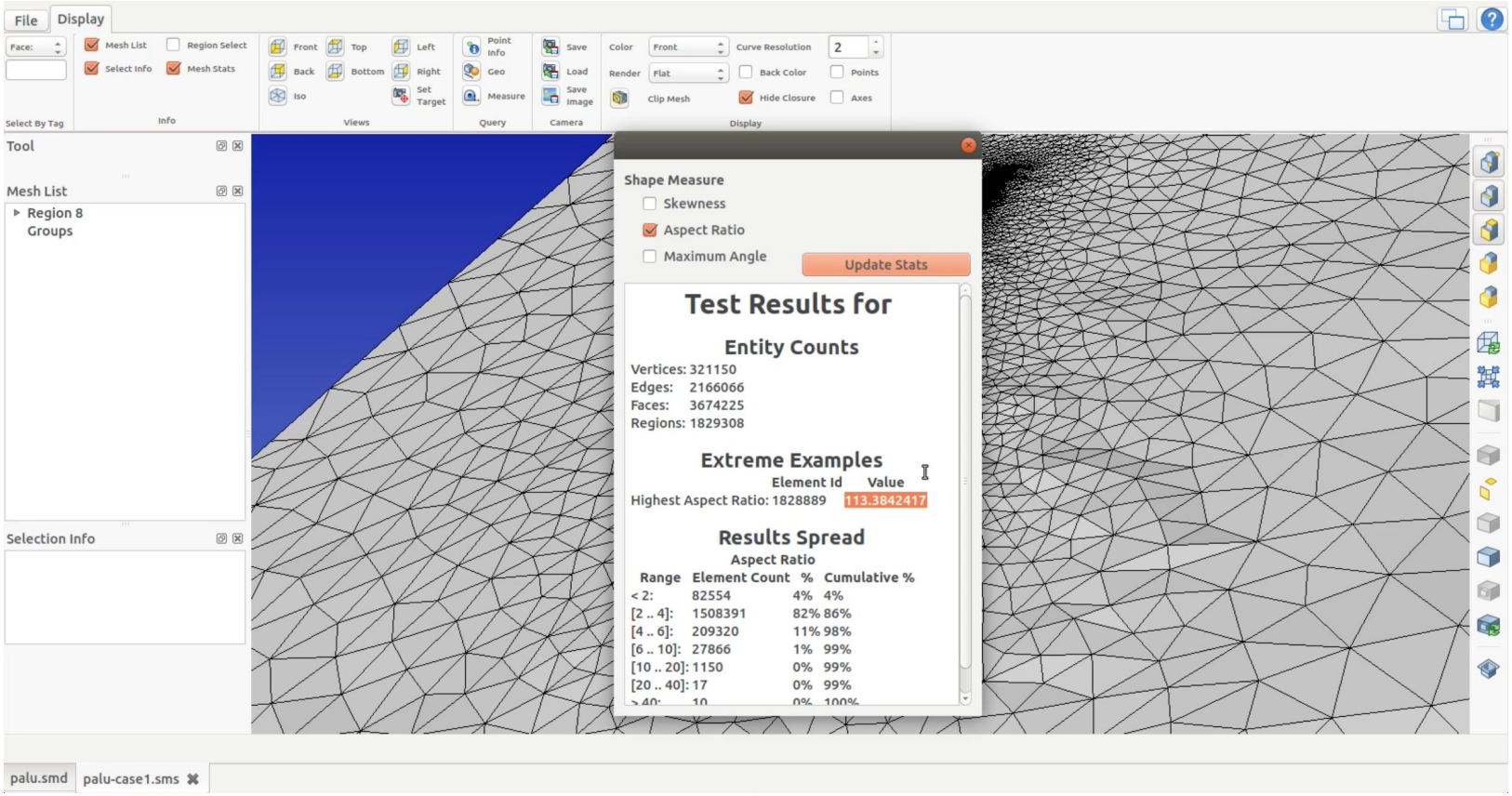
Then save (.smd) file and select **'Generate Mesh'** and start meshing.

Evaluating the mesh

After the meshing is completed, select **'Show Mesh'.**

We can see the mesh statistics by selecting **'Mesh Stats'.**




File
Display
Face:
Mesh List
Region Select
Select Info
Mesh Stats
Select By Tag
Info
Front
Top
Left
Back
Bottom
Right
Iso
Set Target
Views
Point Info
Geo
Measure
Query
Save
Load
Save image
Camera
Color
Front
Curve Resolution
2
Render
Flat
Back Color
Points
Clip Mesh
Hide Closure
Axes
Display
Tool
Mesh List
Region 8
Groups
Selection Info
Shape Measure
Skewness
Aspect Ratio
Maximum Angle
Update Stats
Test Results for
Entity Counts
Vertices: 321150
Edges: 2166066
Faces: 3674225
Regions: 1829308
Extreme Examples
Element Id Value
Highest Aspect Ratio: 1828889 113.3842417
Results Spread
Aspect Ratio
Range Element Count % Cumulative %
< 2: 82554 4% 4%
[2 .. 4]: 1508391 82% 86%
[4 .. 6]: 209320 11% 98%
[6 .. 10]: 27866 1% 99%
[10 .. 20]: 1150 0% 99%
[20 .. 40]: 17 0% 99%
palu.smd
palu-case1.sms

and then we save the generated mesh file (.neu).

Note that we recommend meshing using **PUMGen** for creating and exporting meshes in an efficient format (**PUML**). We can use the mesh analysis file (.smd) as the input or convert it from the ASCII mesh (.neu) file.