

3D Modelling of the In-Situ Stress Field in Nordland, Northern Norway

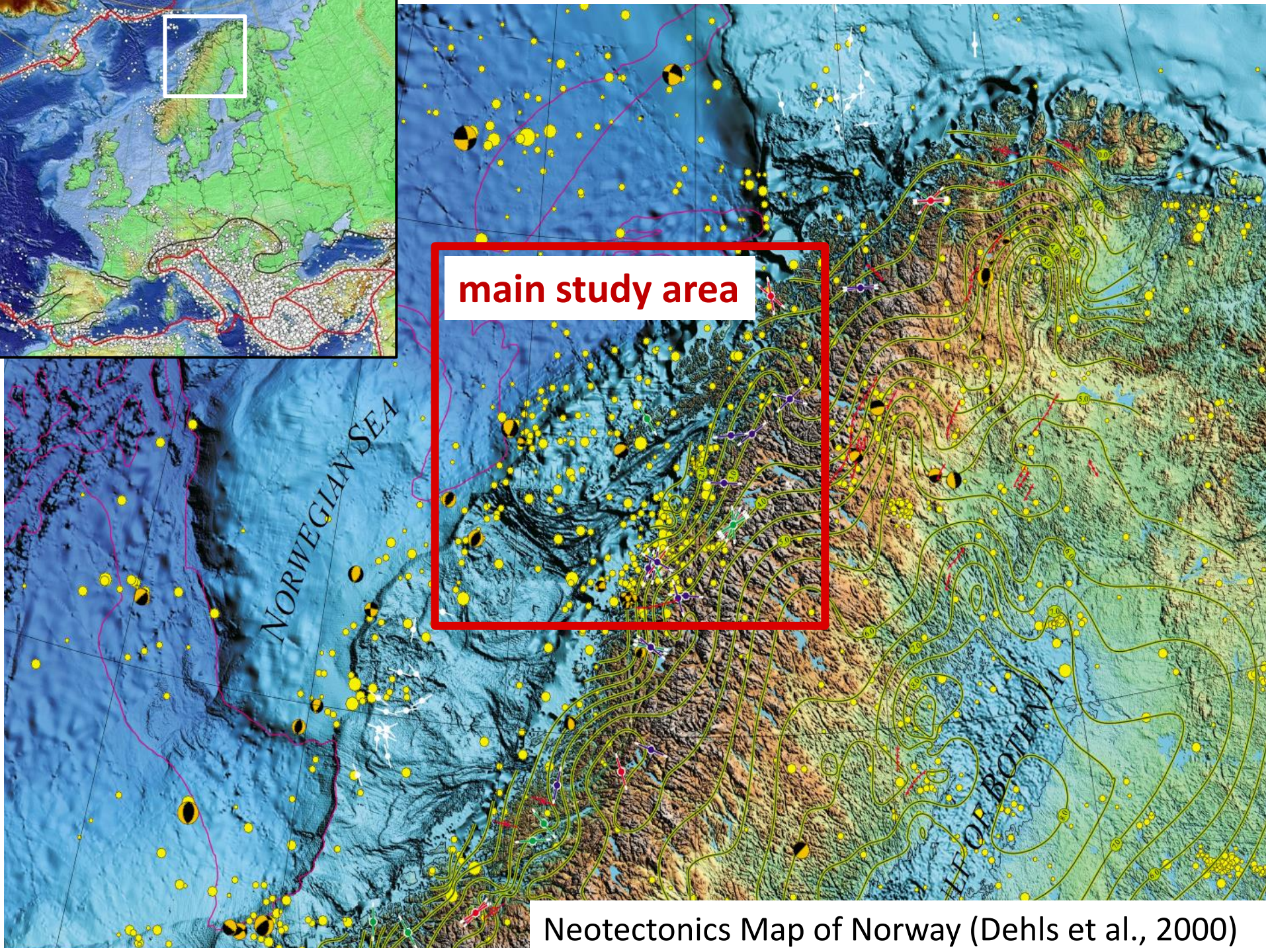
Sofie Gradmann, Yuriy Maystrenko,
Marie Keiding, Odleiv Olesen



GEOLOGICAL SURVEY OF NORWAY

- NGU -

**COMSOL
CONFERENCE**
2017 ROTTERDAM
OCTOBER 18th-20th



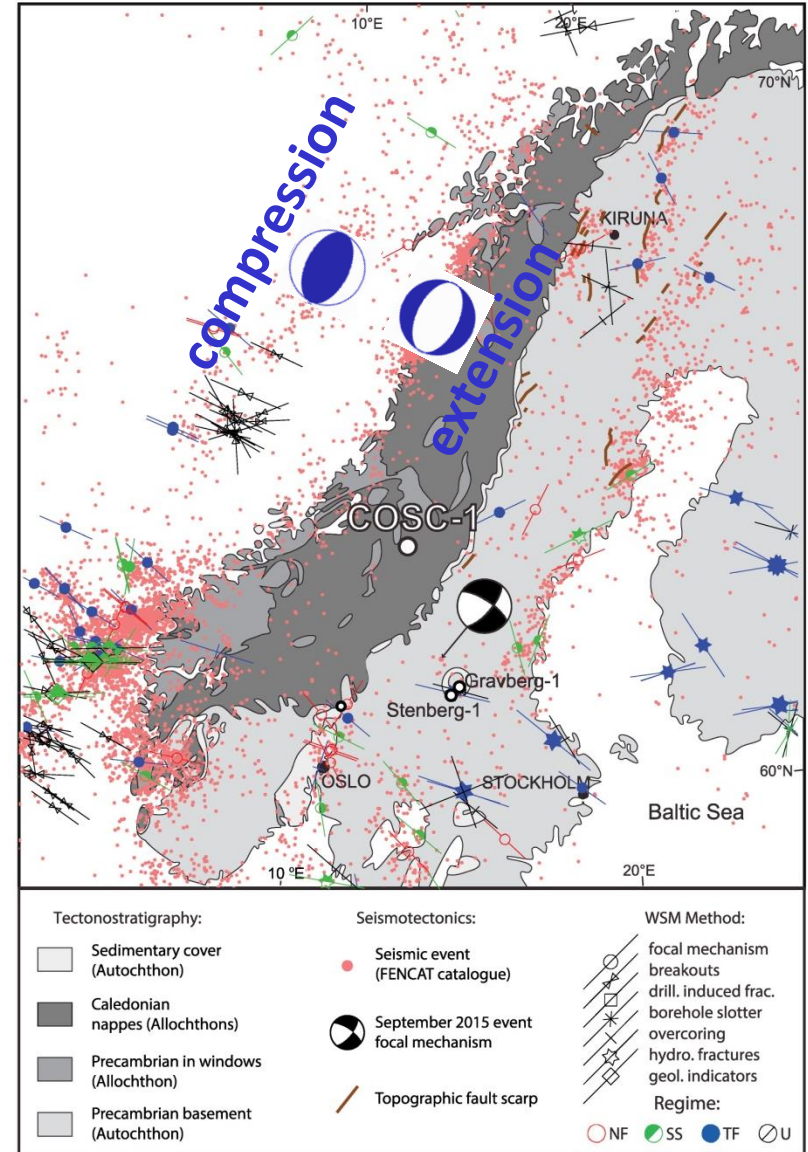
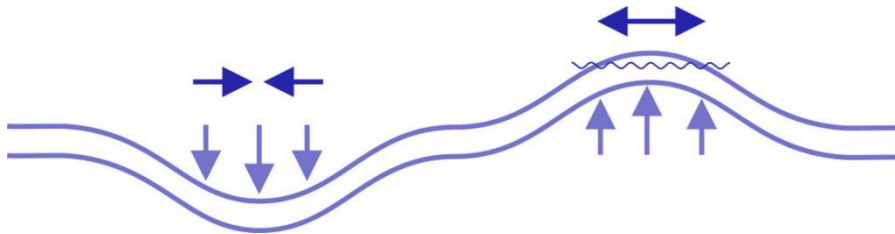
main study area

Neotectonics Map of Norway (Dehls et al., 2000)



Present-Day Stress Regime

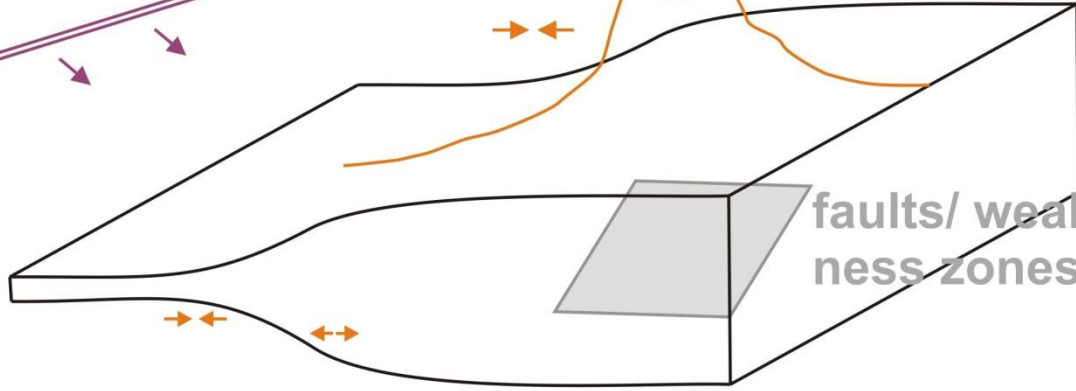
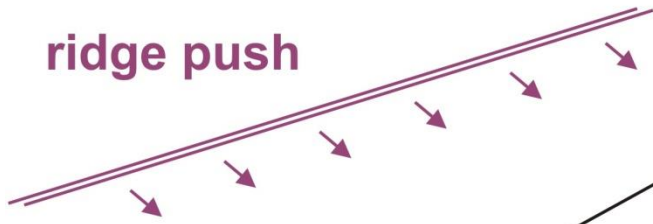
- primarily WNW-ESE
 - unaffected by Eurafrican collision
 - compression offshore
 - extension along coast
- Is seismicity linked to flexural effects of sediment re-distribution?





Stress-Field Components

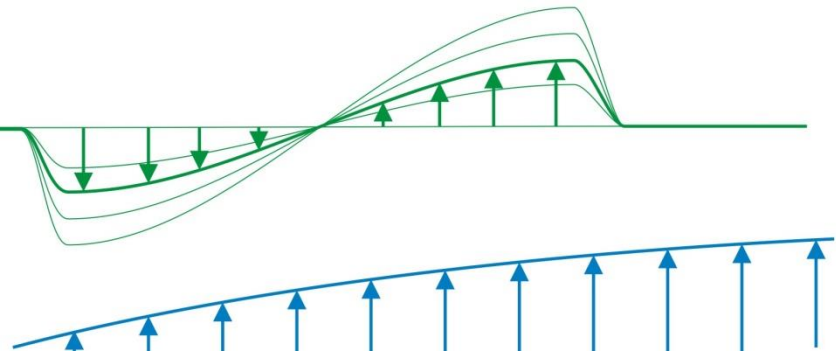
gravitational stresses
(e.g. topographic)



faults/ weakness zones

loading/unloading

GIA



gravi-tational + ridge push + GIA + sed. load. = present-day stress field



Modelling Approach

3D finite element modelling with COMSOL Multiphysics®

- Structural Mechanics Module
- Geomechanics Module

3D model

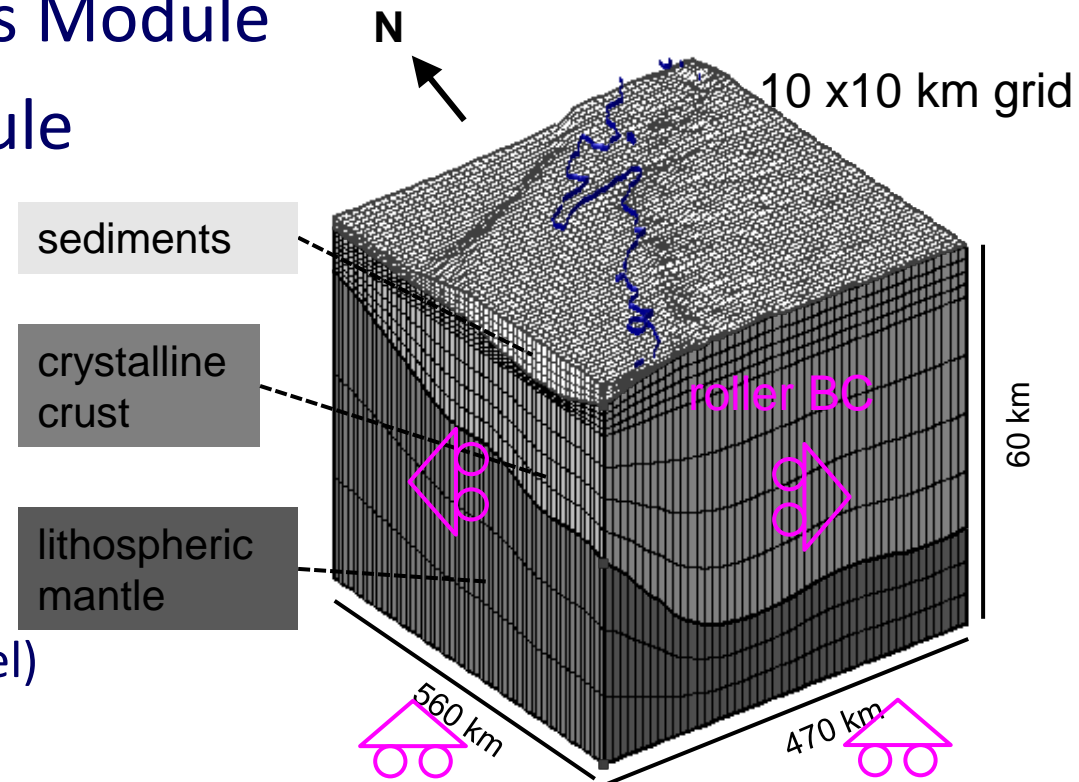
Gravity (uniaxial compression)

Rheology (linear elastic)

Material properties (ρ , E , ν)

Boundary Conditions (basic model)

- roller BC @ sides
- roller BC @ bottom
- water load @ top

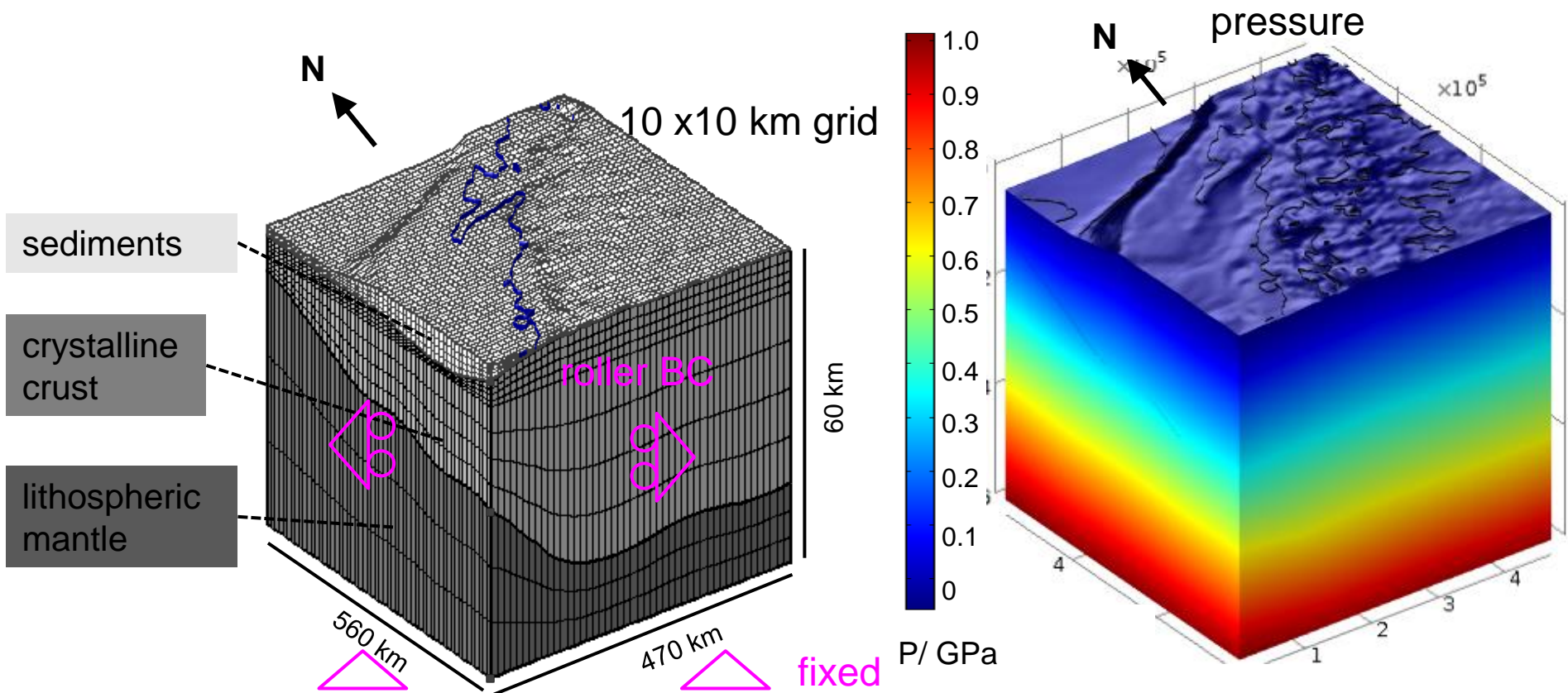




Material Properties

	Density	Rheology (linear elastic)
sediments	2700 kg/m ³	E=40GPa, v=0.3
cryst. crust	2800 kg/m ³	E=60GPa, v=0.3
lith. mantle	3300 kg/m ³	E=70GPa, v=0.3

water load &
+ gravity



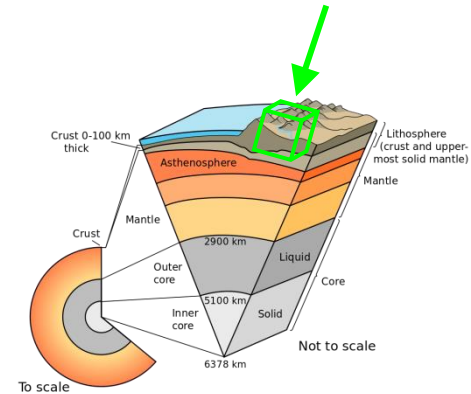
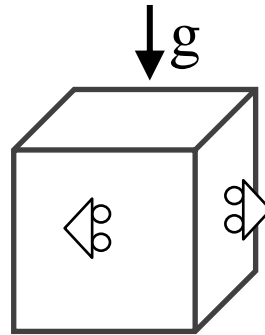


Modelling the Regional 3D Stress-Field

Model

vs.

Earth



**Problem 1 –
rheology**

**elastic
deformation**

**no deformation
complex rheology**

**Problem 2 –
background stress**

tensile

near-lithostatic

**Problem 3 –
stresses at surface**

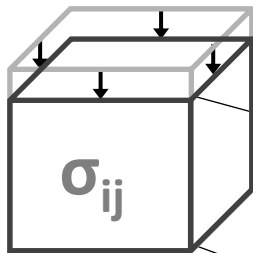
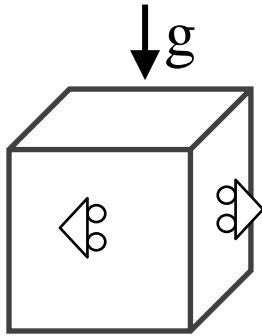
poorly resolved

highly variable



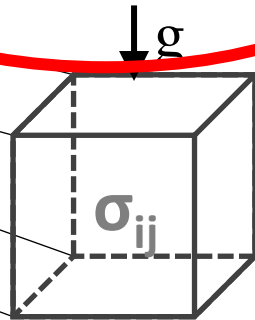
Problem 1 – Displacement/Rheology

Model



stresses σ_{ij} and
LARGE
displacement

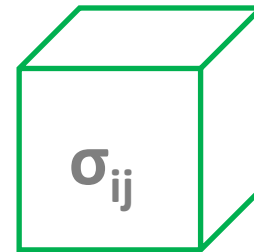
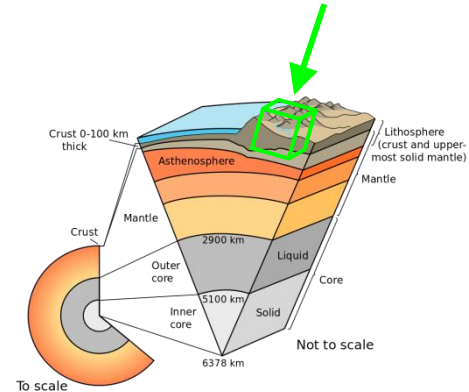
Solution1:
pre-stress with σ_{ij}



stresses σ_{ij} and
negligible
displacement

vs.

Earth



stresses σ_{ij} +
no displacement



Basic Model – total displacement

0. run basic model
1. export full stress tensor
2. import stress tensor as interpolation function
3. use imported values as initial stress

The screenshot shows the COMSOL Model Builder interface. The left pane displays the model tree, where 'Initial Stress and Strain from 1. run' is highlighted with a red circle. The right pane shows the 'Initial Stress and Strain' settings, with the 'Initial Stress' table also highlighted by a red circle.

Initial Stress and Strain

Label: Initial Stress and Strain from 1. run

Domain Selection

Selection: All domains

Active: 1, 2, 3, 4

Equation

Show equation assuming: Study1 - basic model, Stationary

$$\mathbf{s} - \mathbf{s}_0 = \mathbf{C} : (\boldsymbol{\epsilon} - \boldsymbol{\epsilon}_0 - \boldsymbol{\epsilon}_{inel}) - (\text{trace}(\mathbf{C} : (\boldsymbol{\epsilon} - \boldsymbol{\epsilon}_0 - \boldsymbol{\epsilon}_{inel}))/3 + p_w)\mathbf{I}$$

Coordinate System Selection

Coordinate system: Global coordinate system

Initial Stress and Strain

Initial stress:

$S_{sx}(x,y,z)$	$S_{sxy}(x,y,z)$	$S_{sxz}(x,y,z)$	N/m ²
$S_{sxy}(x,y,z)$	$S_{sy}(x,y,z)$	$S_{syz}(x,y,z)$	
$S_{sxz}(x,y,z)$	$S_{syz}(x,y,z)$	$S_{sz}(x,y,z)$	

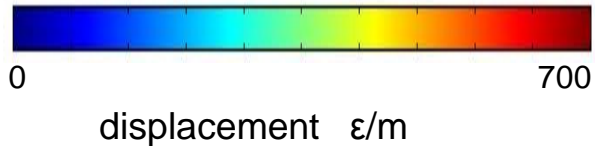
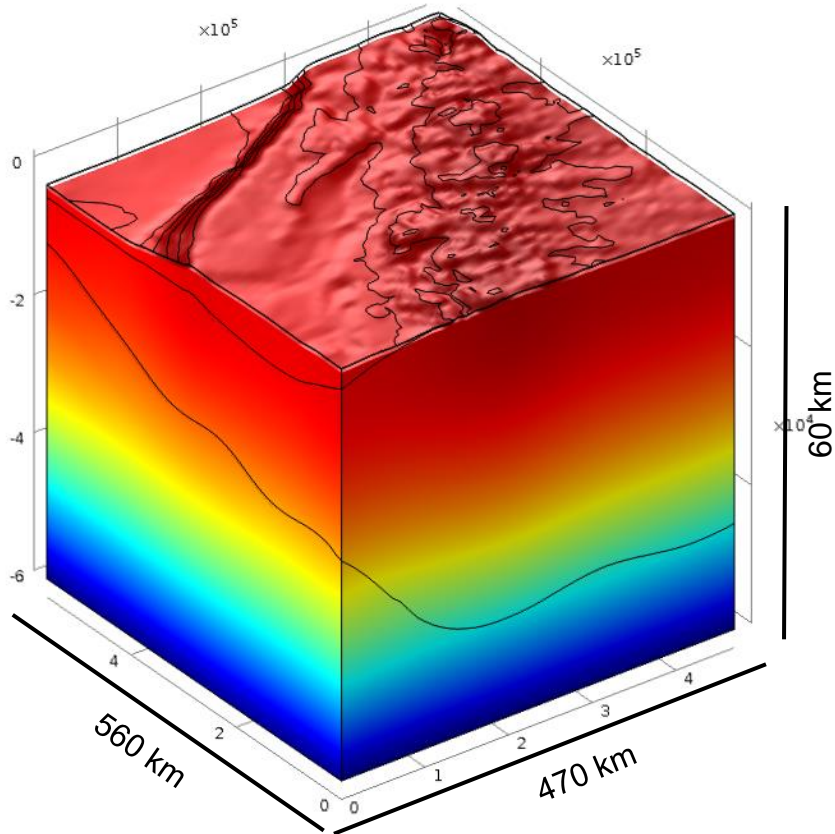
Initial strain:

0	0	0	1
0	0	0	
0	0	0	

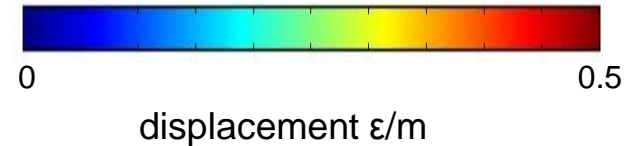
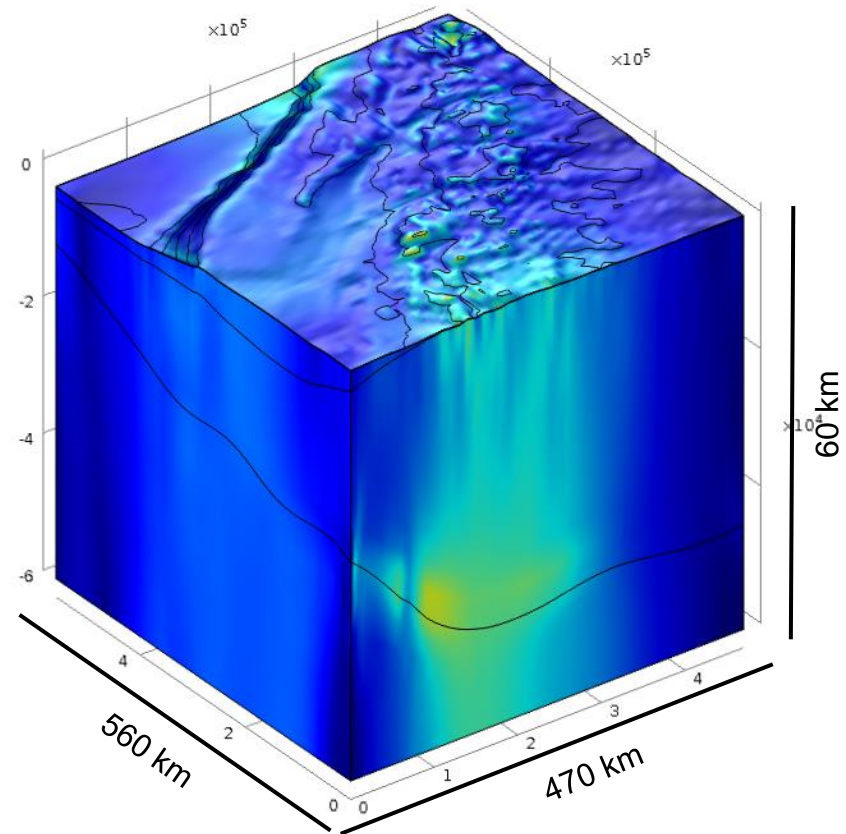


Pre-Stressing and Deformation

basic model



basic model with pre-stressing





Problem 2 – Background Stress

Model

linear elastic material

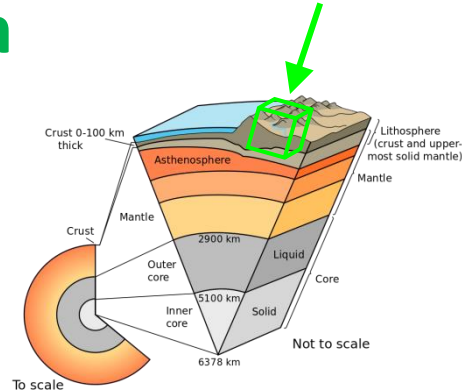
Young's modulus E

Poisson ratio ν

vs.

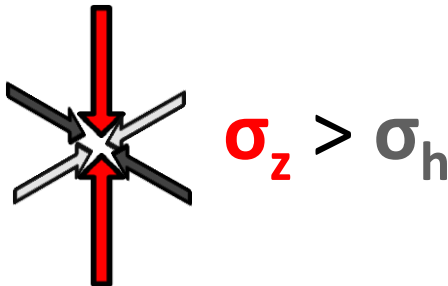
Earth

stresses in uniaxial compression



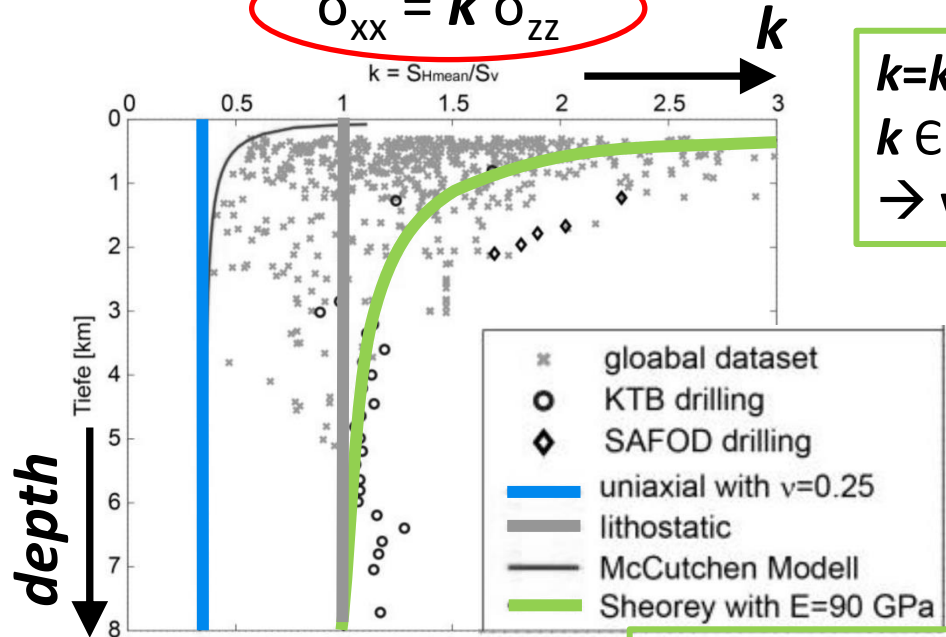
$$\sigma_{xx} = k \sigma_{zz}$$

$$k = \nu / (1 - \nu)$$
$$k = \text{const}$$



$$\sigma_z > \sigma_h$$

$$k = k(z)$$
$$k \in [0.33, 3]$$
$$\rightarrow \nu \in [0.25, 0.75]$$



Hegert and Heidbach, 2011

Sheorey, 1994

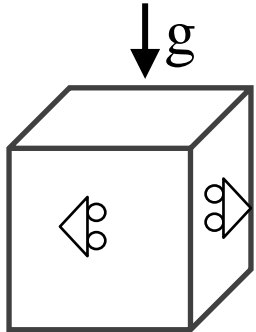
$$k = 0.25 + 7 * E * (0.001 + 1/z)$$

$k < 1$, tension $k = 1$, lithostatic $k > 1$, compression



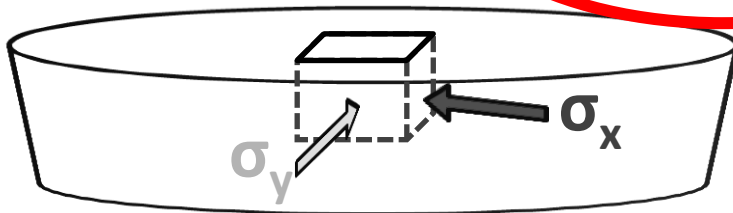
Solution 2 – Background Stress

Model



Solution2:

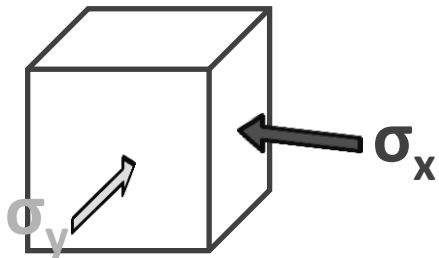
1. embed model in box with tilted edges (spherical Earth)



Sheorey Box

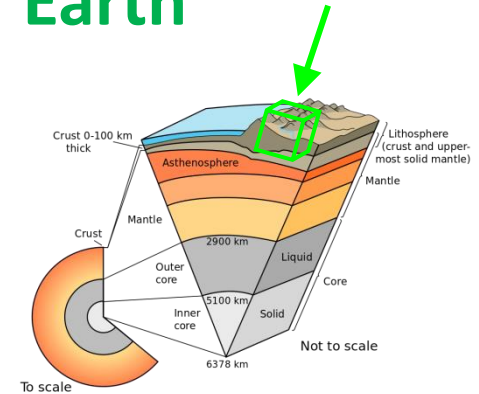
2. extract stresses within model box

3. apply these stresses as pre-stress on small box



vs.

Earth

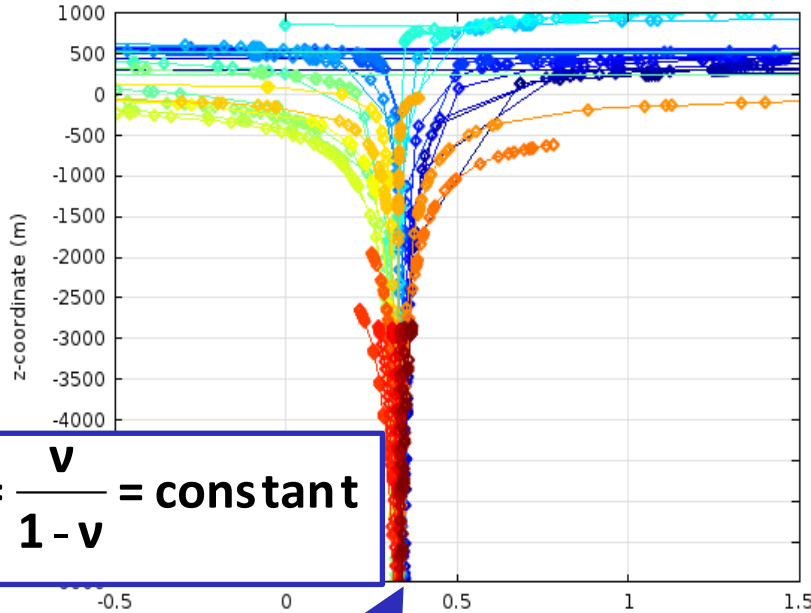




Basic Model – Background Stress

$k(z)$

without Sheorey Box stresses

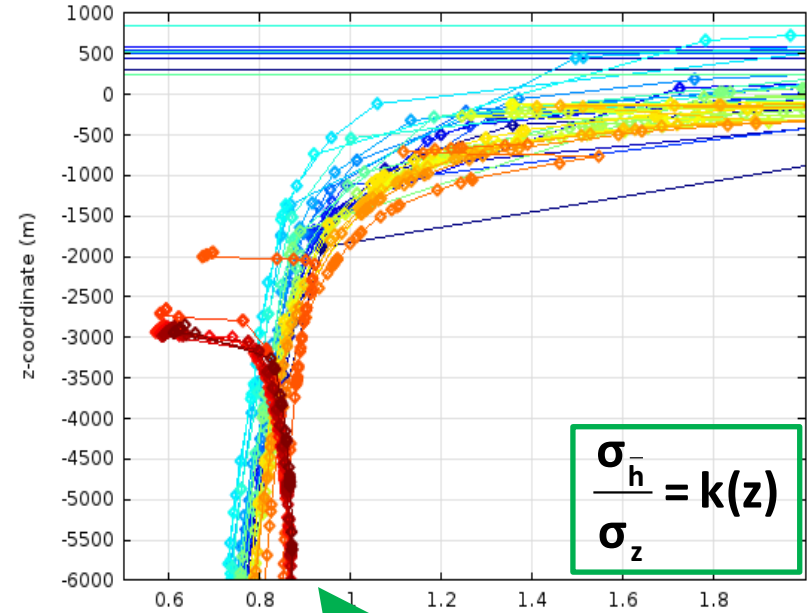


$$\frac{\sigma_h}{\sigma_z} = \frac{\nu}{1-\nu} = \text{constant}$$

$k_{\text{deep}}=0.33$

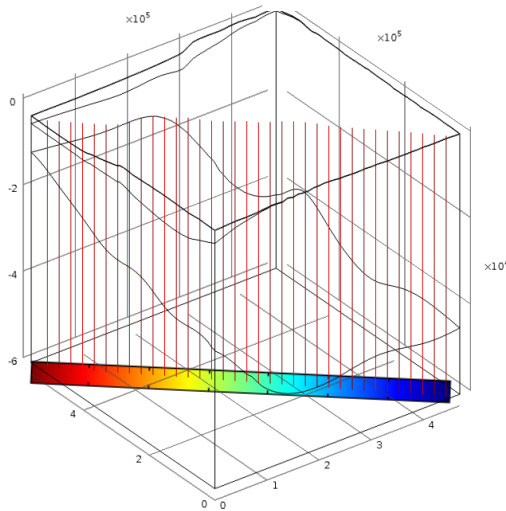
$k(z)$

with Sheorey Box stresses



$$\frac{\sigma_h}{\sigma_z} = k(z)$$

$k_{\text{deep}} \approx 0.8$





Background Stress - Alternative solution

Model Builder

neonor2_2017-10_simplemodel-L1_approachPreStress.mph (root)

- Global
- Model 1 (mod1)
 - Definitions
 - some variables
 - pre-stresses from 1. run (S_sx ...)
 - depth to seafloor (z_seafloor)
 - Boundary System 1 (sys1)
 - View 1
 - Geometry 1
 - Materials
 - Sediments In, UpperCrust 1 (mat12)
 - Granite In, UpperCrust (mat6)
 - Granite In, Mantle (mat11)

Settings Properties

Variables

Label: some variables

Geometric Entity Selection

Geometric entity level: Entire model

ON

Active

Name	Expression	Unit	Description
E_GPa	solid4.E * 1e-9	Pa	Youngs modulus in GPa
zburial	z-z_seafloor(z)	m	burial depth
k_z	0.25 + 7* E_GPa * (0.00...	N/m ³	pre-defined k-ratio
nu_z	k_z/(1+k_z)		pre-defined Poisson ratio

$$k = 0.25 + 7 * E * (0.001 + 1/z)$$

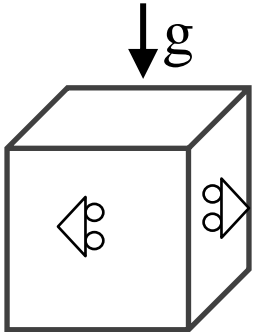
$$\rightarrow \nu \in [0.25, 0.75]$$

Sheorey, 1994



Background Stress - Alternative Solution

Model

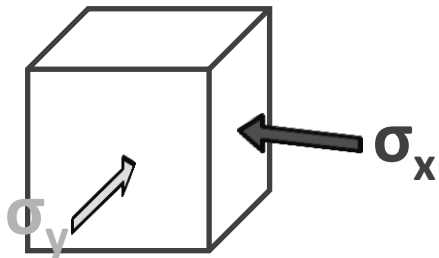


Solution2b:

1. run model with depth-dependent Poisson ratio

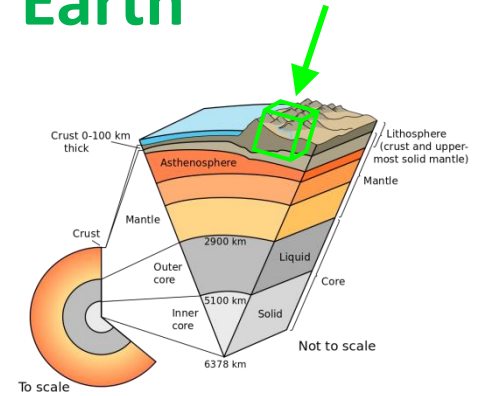
2. extract stresses within model box

3. apply these stresses as pre-stress on small box (with constant Poisson ratios)



vs.

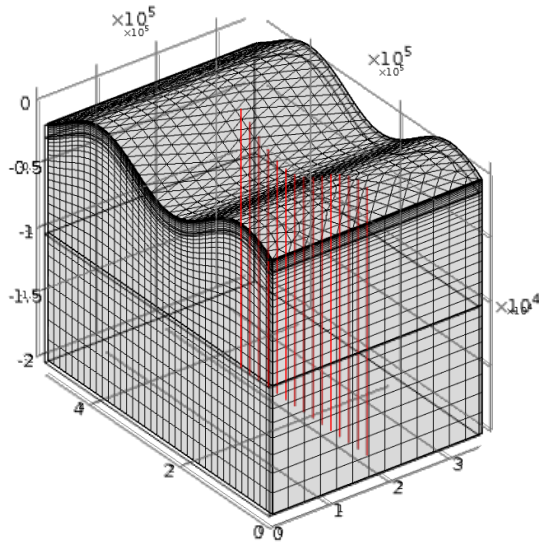
Earth



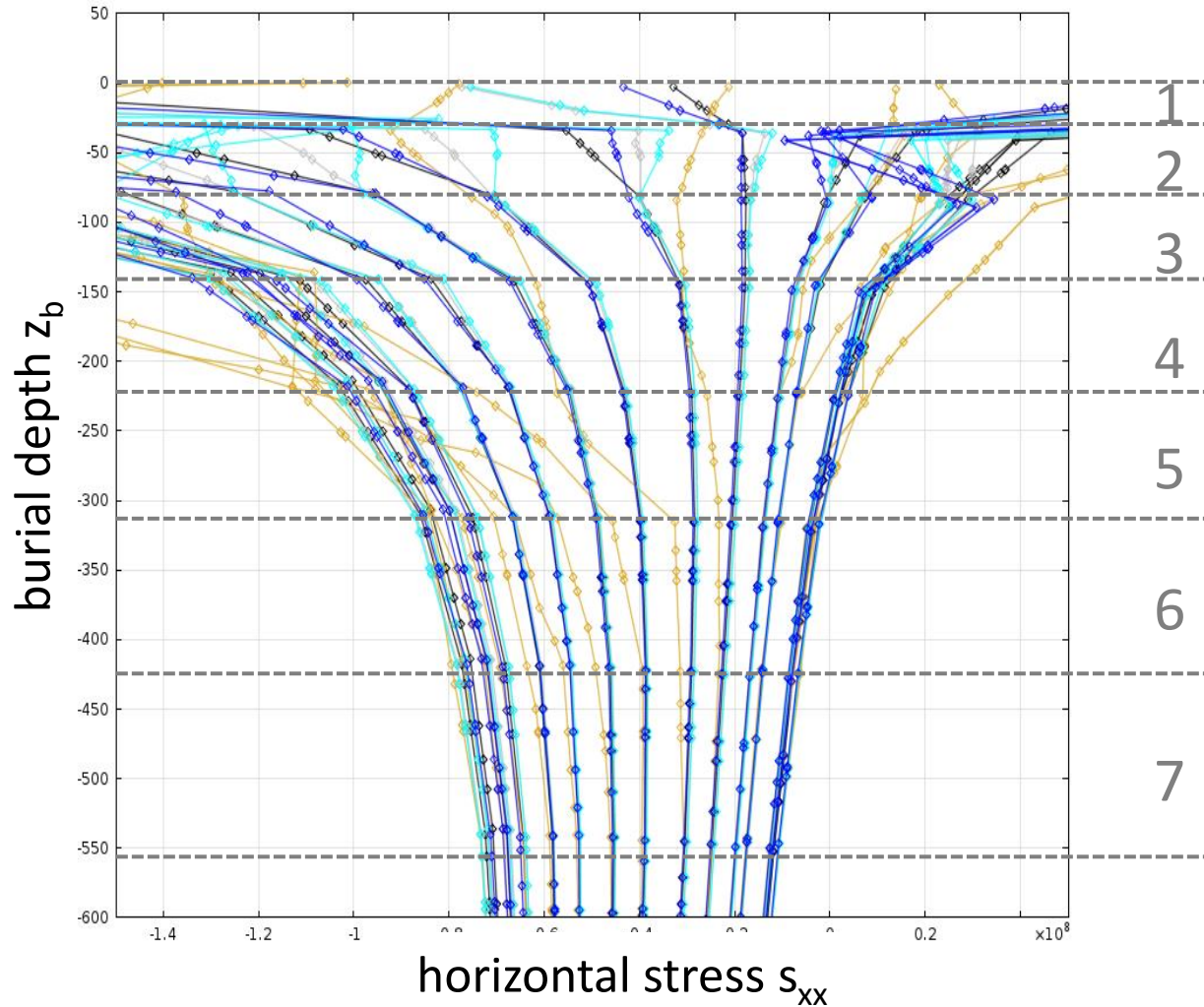


Problem 3 – Stresses @ Surface

element
number



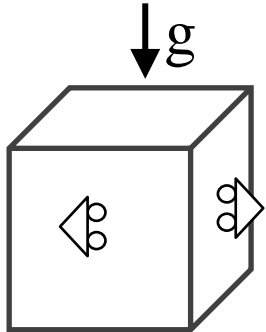
test model





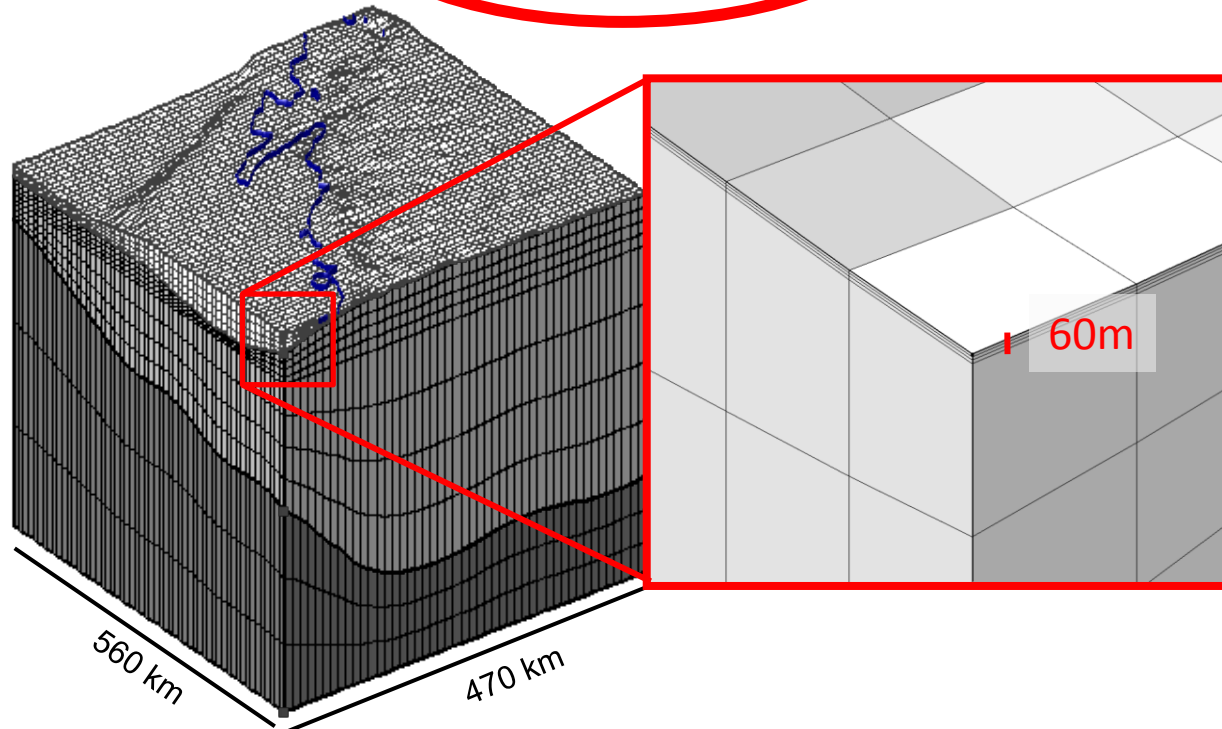
Problem 3 – Stresses @ Surface

Model



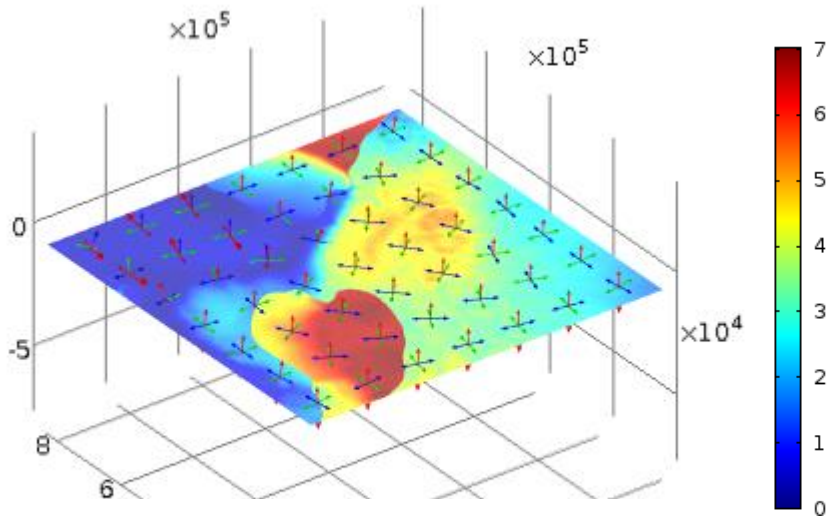
poorly resolved

Solution3:
discard top three
elements

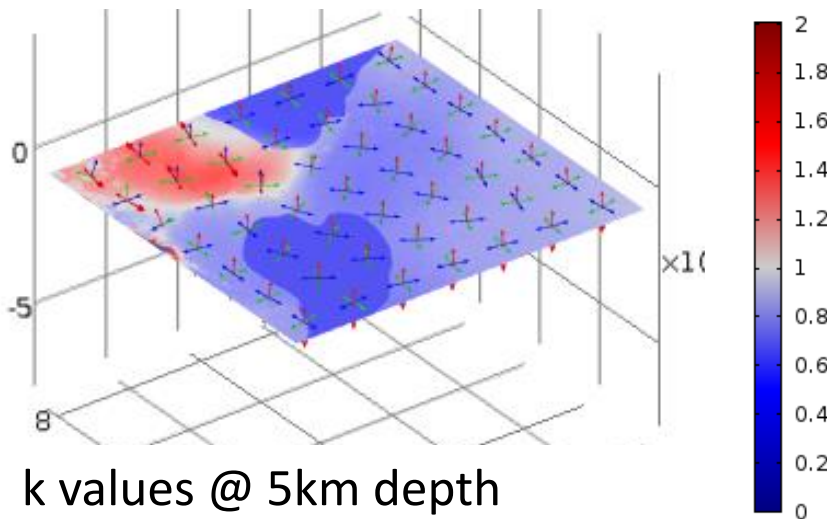




Basic Model – Results and Summary



Von Mises stress @ 5km depth,
principal stress direction



k values @ 5km depth

Problem 1: large elastic deformation

→ **Solution: pre-stressing from initial run**

Problem 2: background stress

→ **Solution: use Sheorey box (or depth-dependent Poisson ratio)**

Problem 3: surface stresses

→ **Solution: discard top elements**



Adding Stress Field Components

Gravitational Stresses (Topography, Moho,...)

- covered by 'basic model'

Ridge Push

- boundary load @ side

Glacial Isostatic Adjustment

- pre-stresses from independent GIA model

Erosion/Sedimentation

- boundary load/deformation @ top

Existing Faults

- thin elastic layer from Geomechanics module



NORWEGIAN SEA

GULF OF BOHEMIA

Thank You