Assessing uncertainty of time-lapse seismic response due to geomechanical deformation

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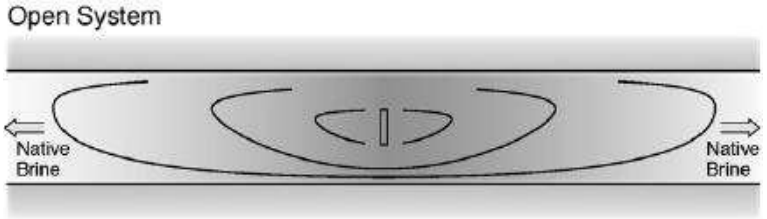
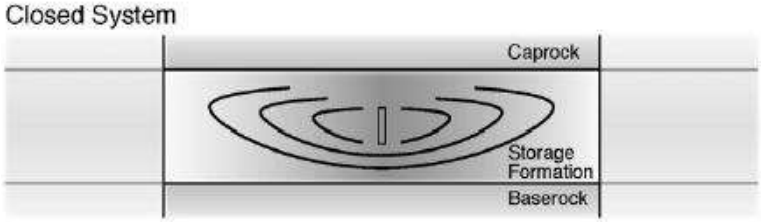
Acknowledgements:
Claire Birnie, Yanxiao He, Tom Lynch & Dave Price

Outline

- Context
- Multi-physics solution
- Time-lapse seismics/geomechanics
- Overburden imaging
- Valhall example
- Geomechanics and uncertainty
- Way forward



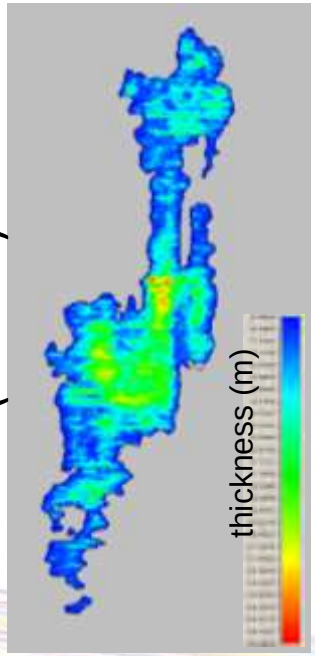


Context

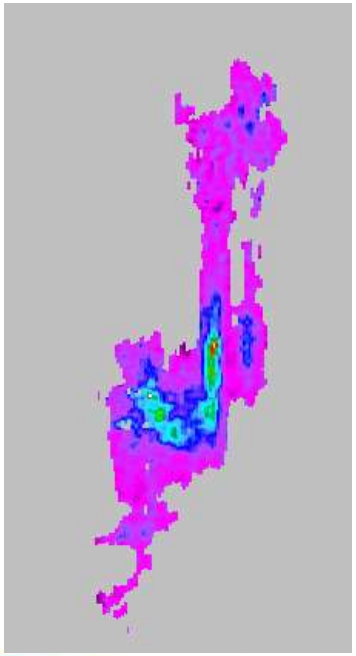
Sleipner

- Negligible pressure effect
- High porosity/high permeability

structural thickness (metres)

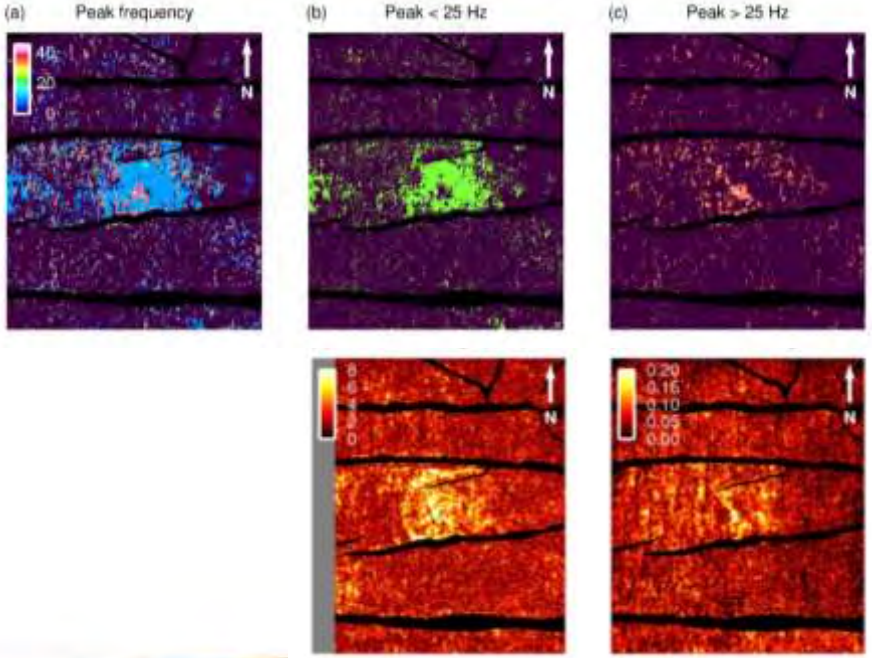


temporal thickness (msec)



Snohvit/In Salah

- Pressure effect
- Snohvit – compartmentalisation
- In Salah - ?



energy

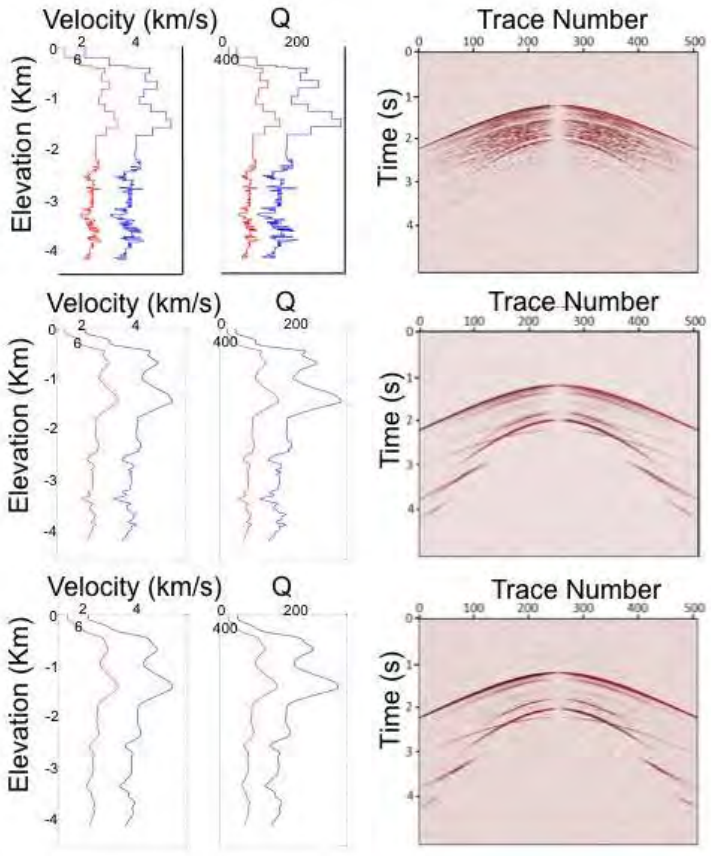
e.g., microseismicity – static velocity model

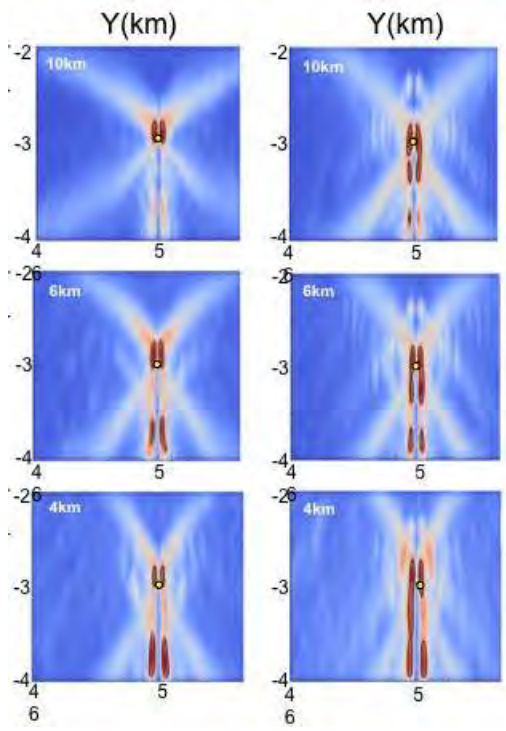
Velocity model

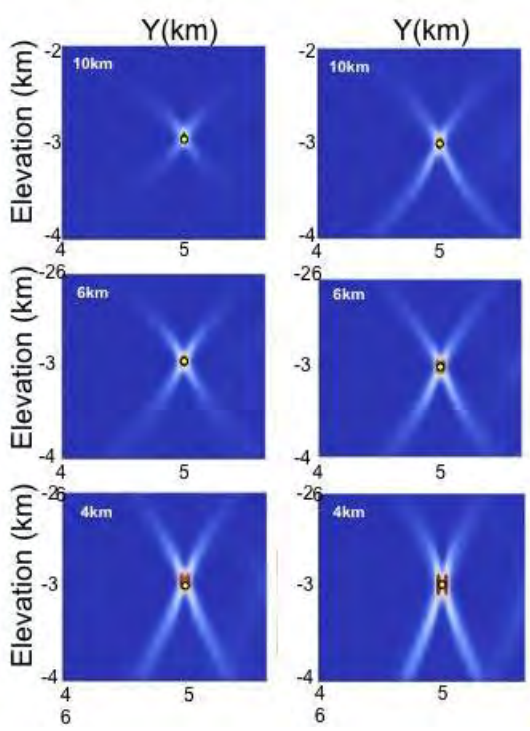
Waveforms

Event location SI

Event location MTMI



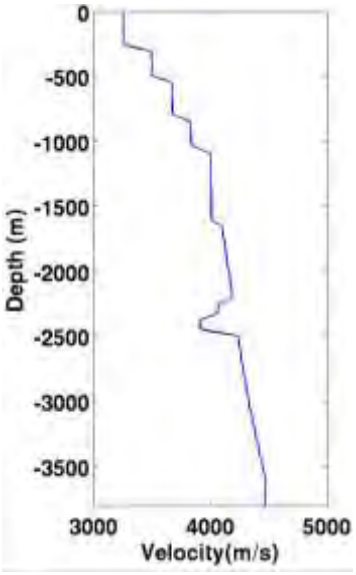




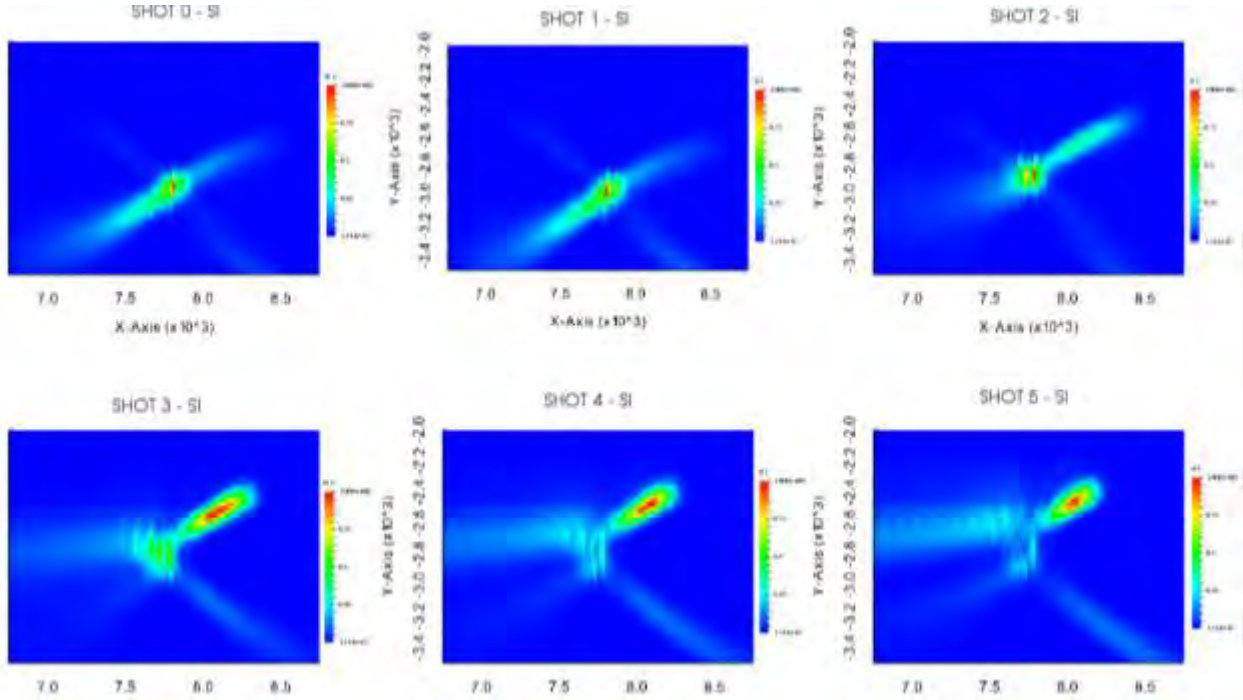
energy

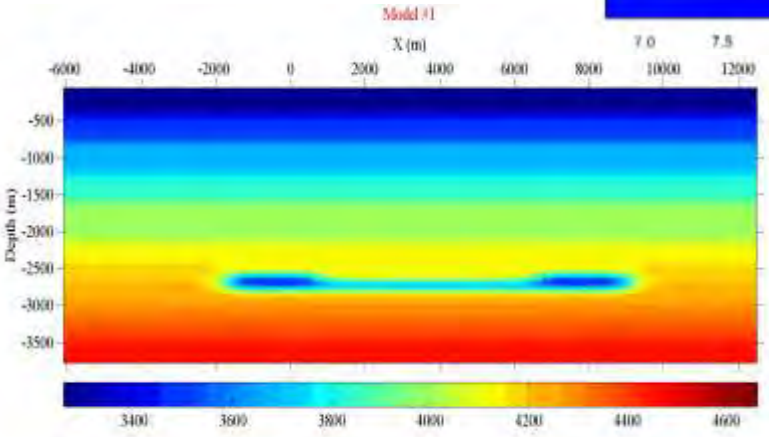
e.g., microseismicity – non-static velocity model

Static velocity model



Event location MTMI





True dynamic velocity model

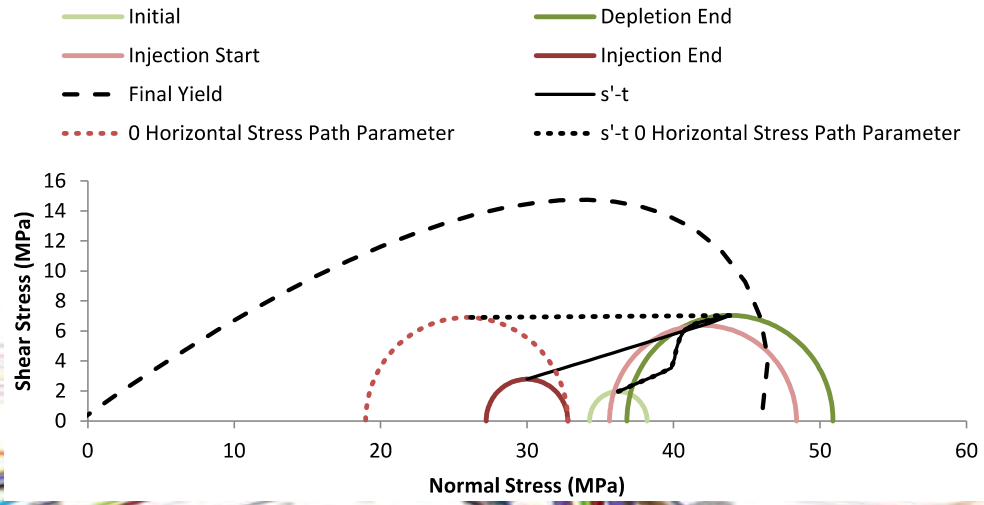
Multi-physics: porous deformable media

- Change in pore pressure (ΔP)

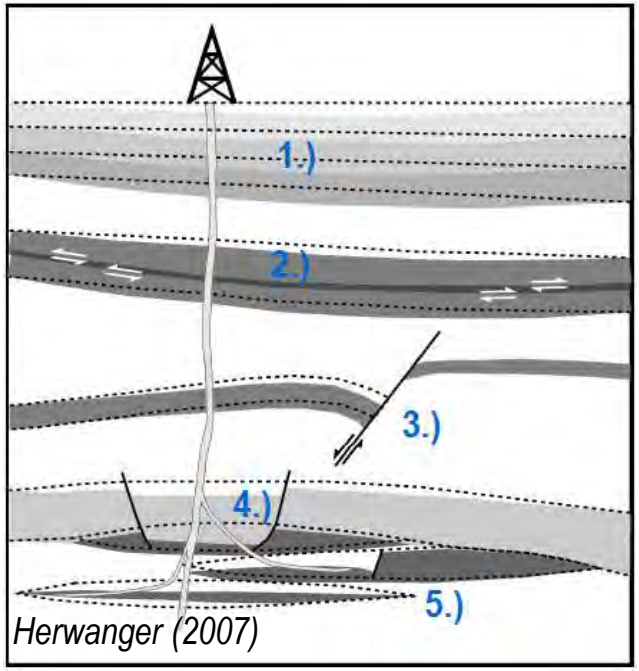
$$\Delta\sigma'_V = \Delta\sigma_V - \alpha\Delta P$$

$$\Delta\sigma'_H = \Delta\sigma_H - \alpha\Delta P$$

- Leads to change in horizontal total stress
- Difficult to predict stress evolution



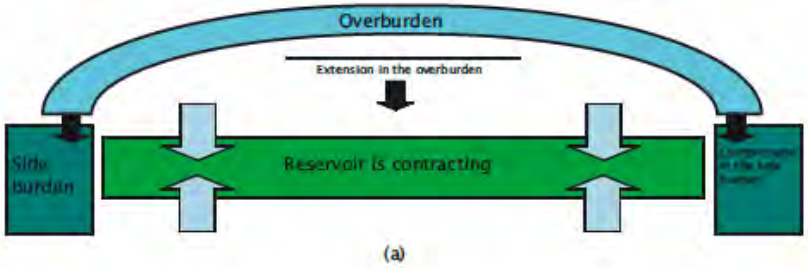
Dynamic view
(syn- and post-production)

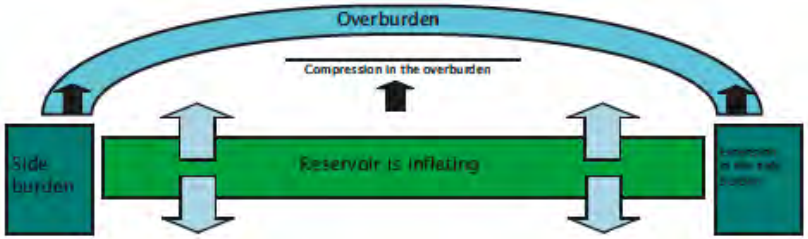


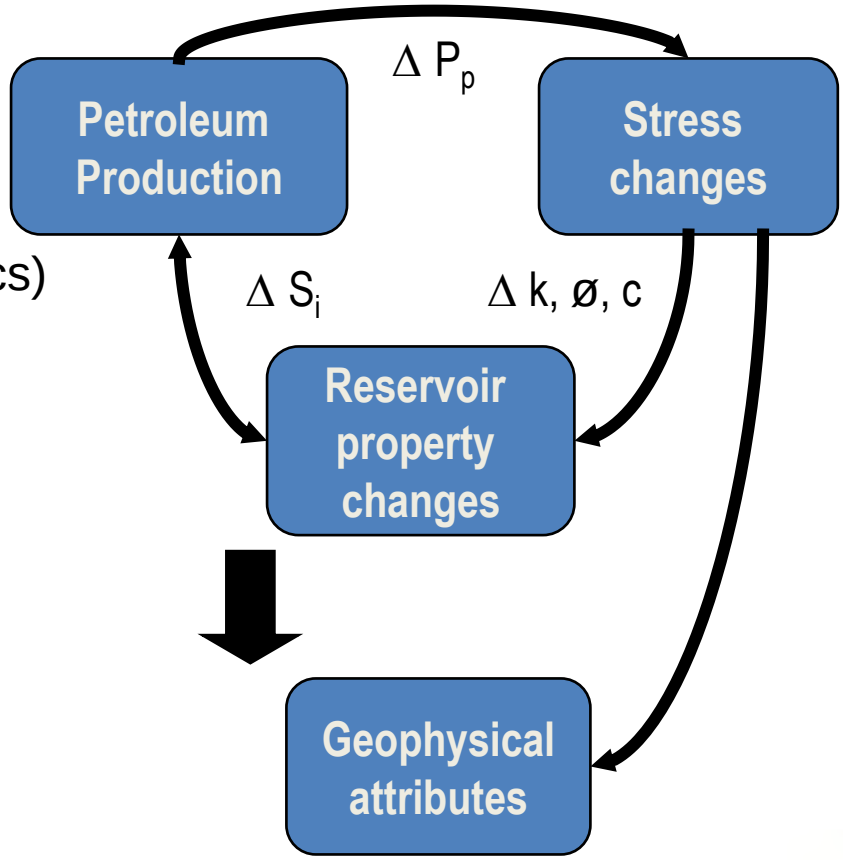
energy

Multi-physics: porous deformable media

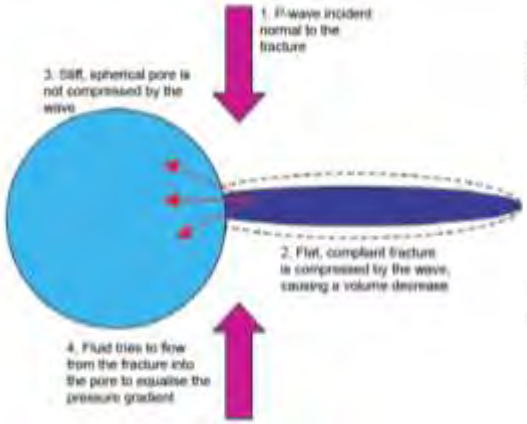
- Integration (hydro-mechanics):
- Coupled fluid-flow/geomechanics
  - Fully-coupled
  - One-way coupling (flow to geomechanics)
  - Two-way coupling







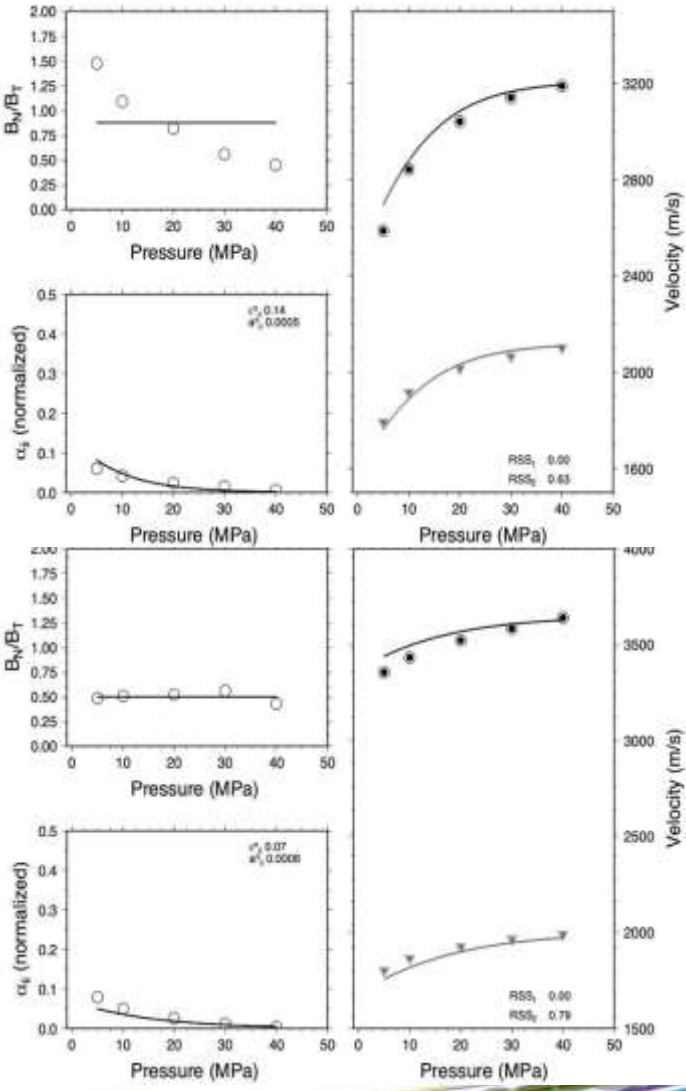
Rock physics transforms



rock physics model

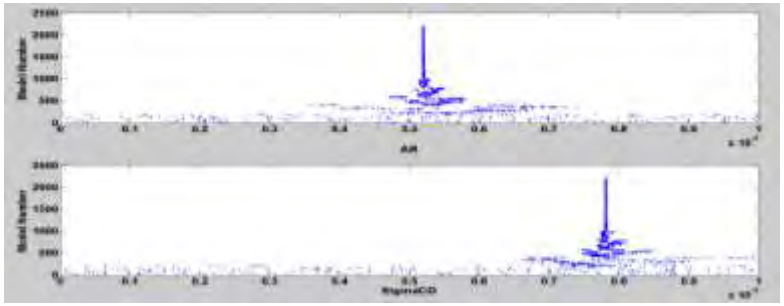
- intrinsic anisotropy → Implement geomathematical model (see Kendall et al., 2007)
- static to dynamic conversion → Not implement yet, but exploring options such as Guyer et al. (1995)
- nonlinear stress dependence → Implement microstructural analytic nonlinear mode (see Verdon et al., 2008)
- fluid effects
  - low frequency → Gassmann's equation (see Brown & Korringa, 1975)
  - frequency effects → Squirtflow model (see Chapman et al., 2002)
- effects of fractures → Implement fracture induced excess compliance and anisotropy (see Hall, 2000, for review)

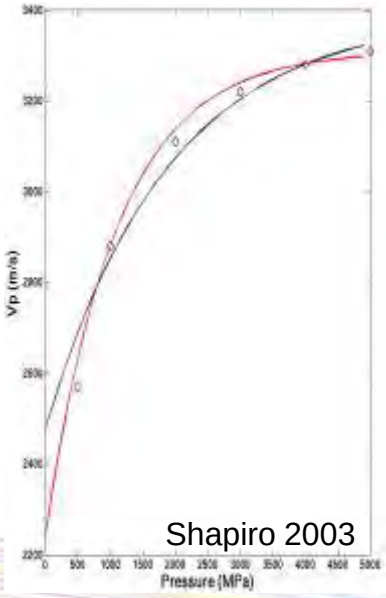
Stress dependent velocities



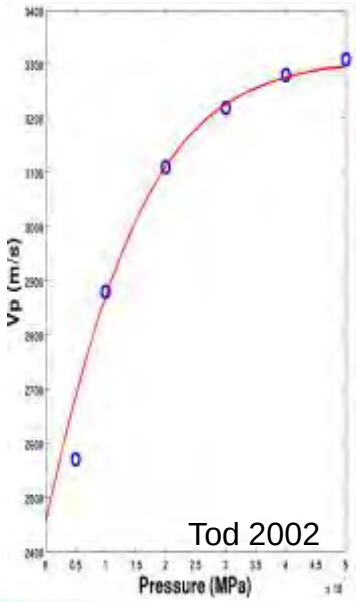
energy

Rock physics



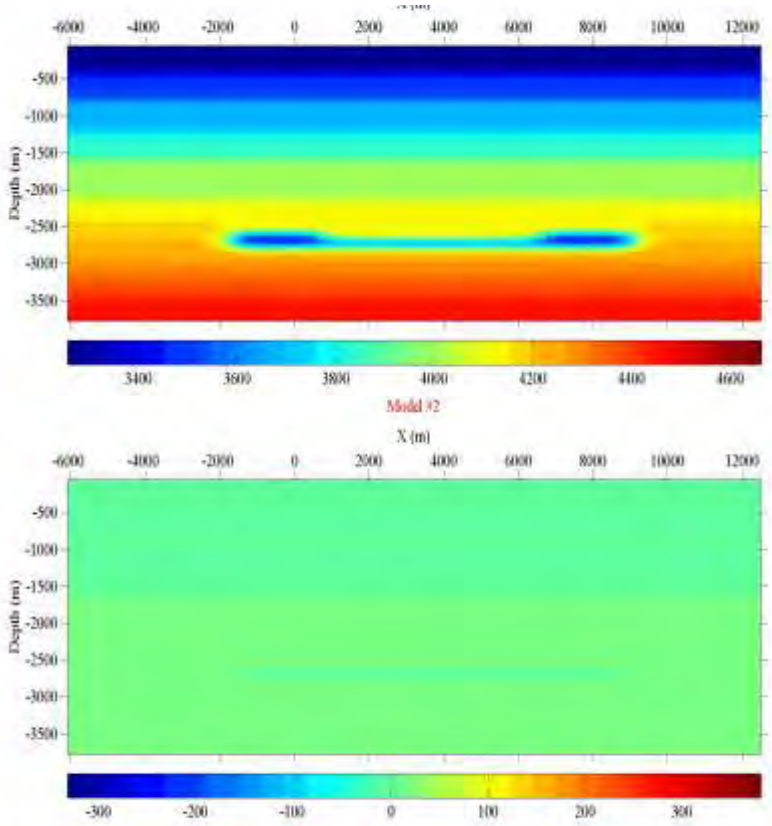


Shapiro 2003



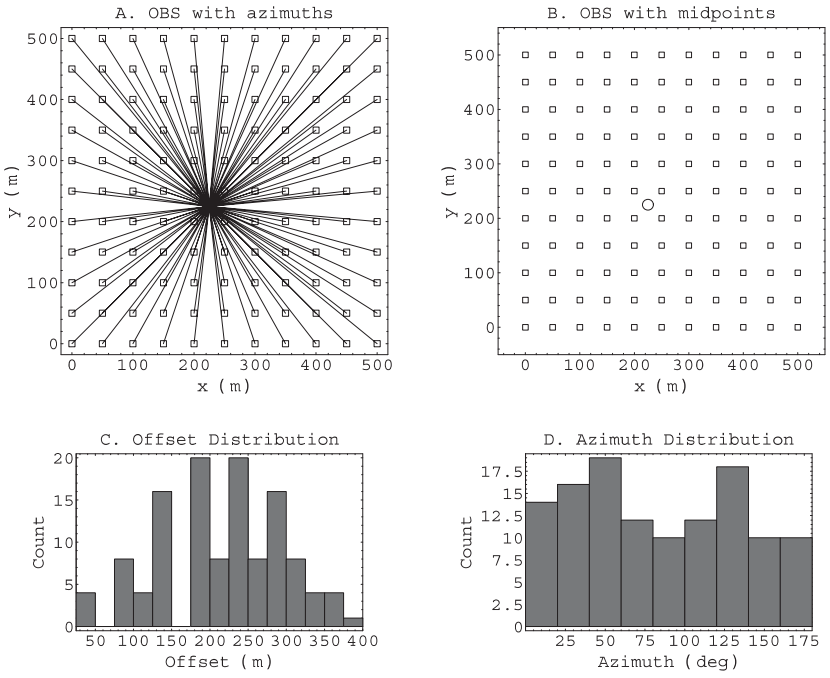
Tod 2002

Reservoir model with high fault transmissibility

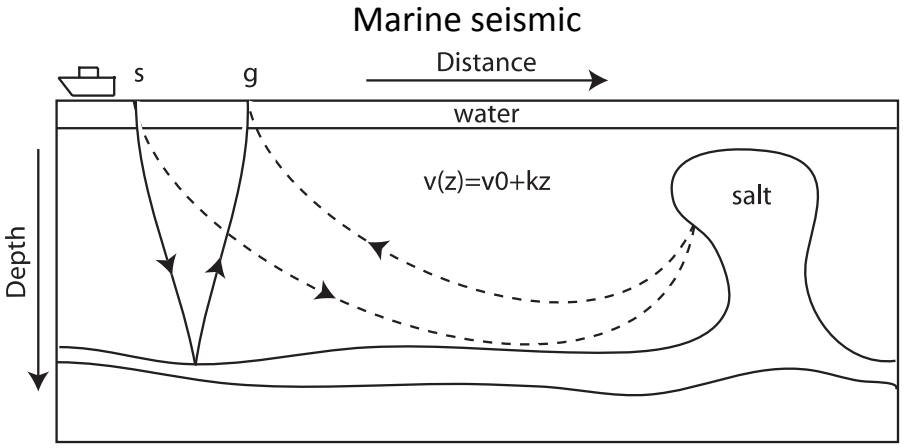


Seismic monitoring

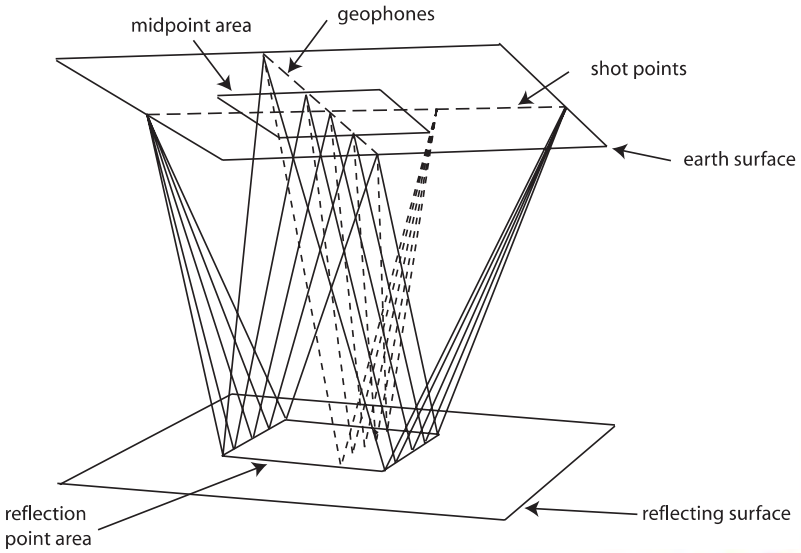
Acquisition (instrument) geometry



Marine seismic

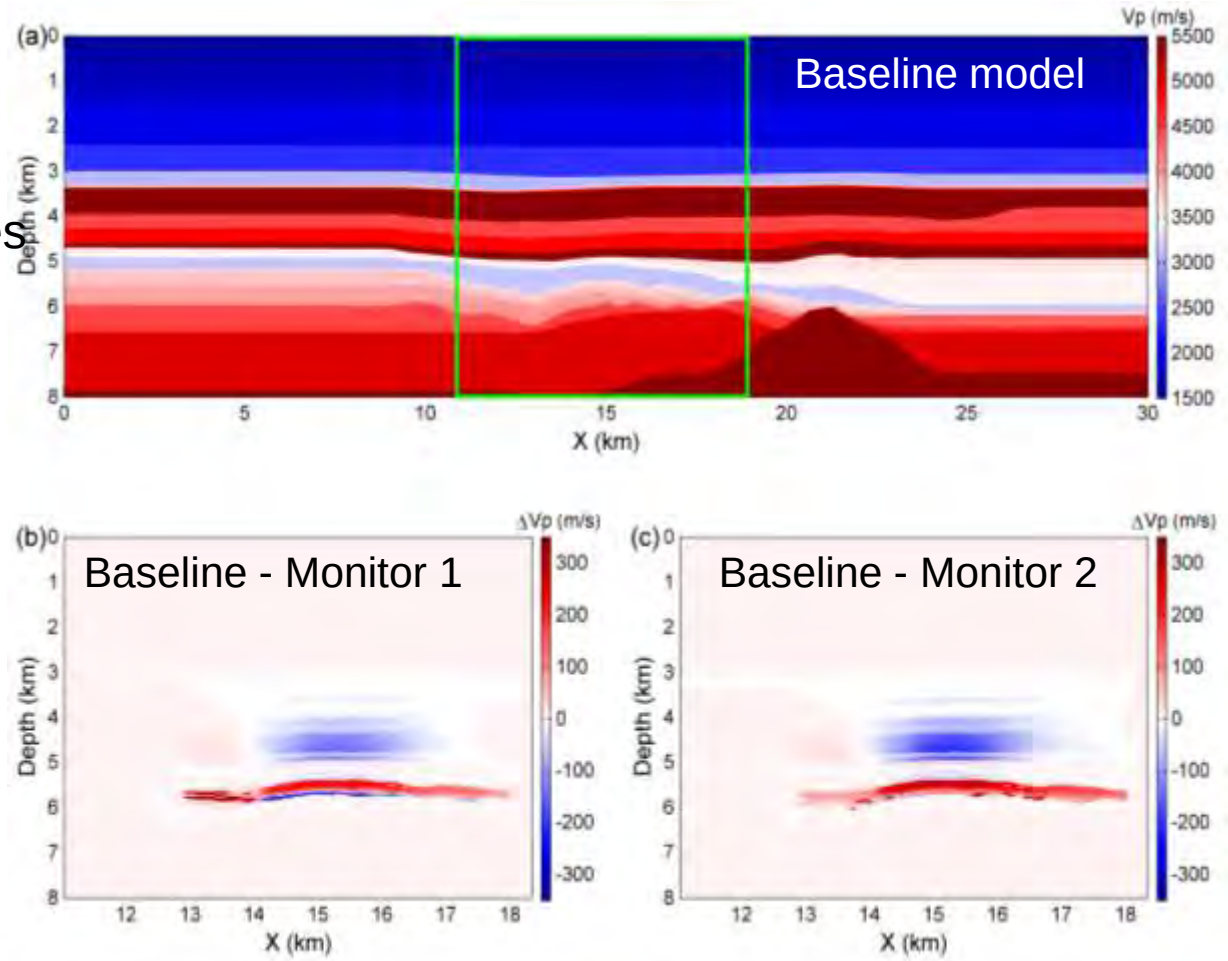


Land seismic



Time-lapse or 4D seismic

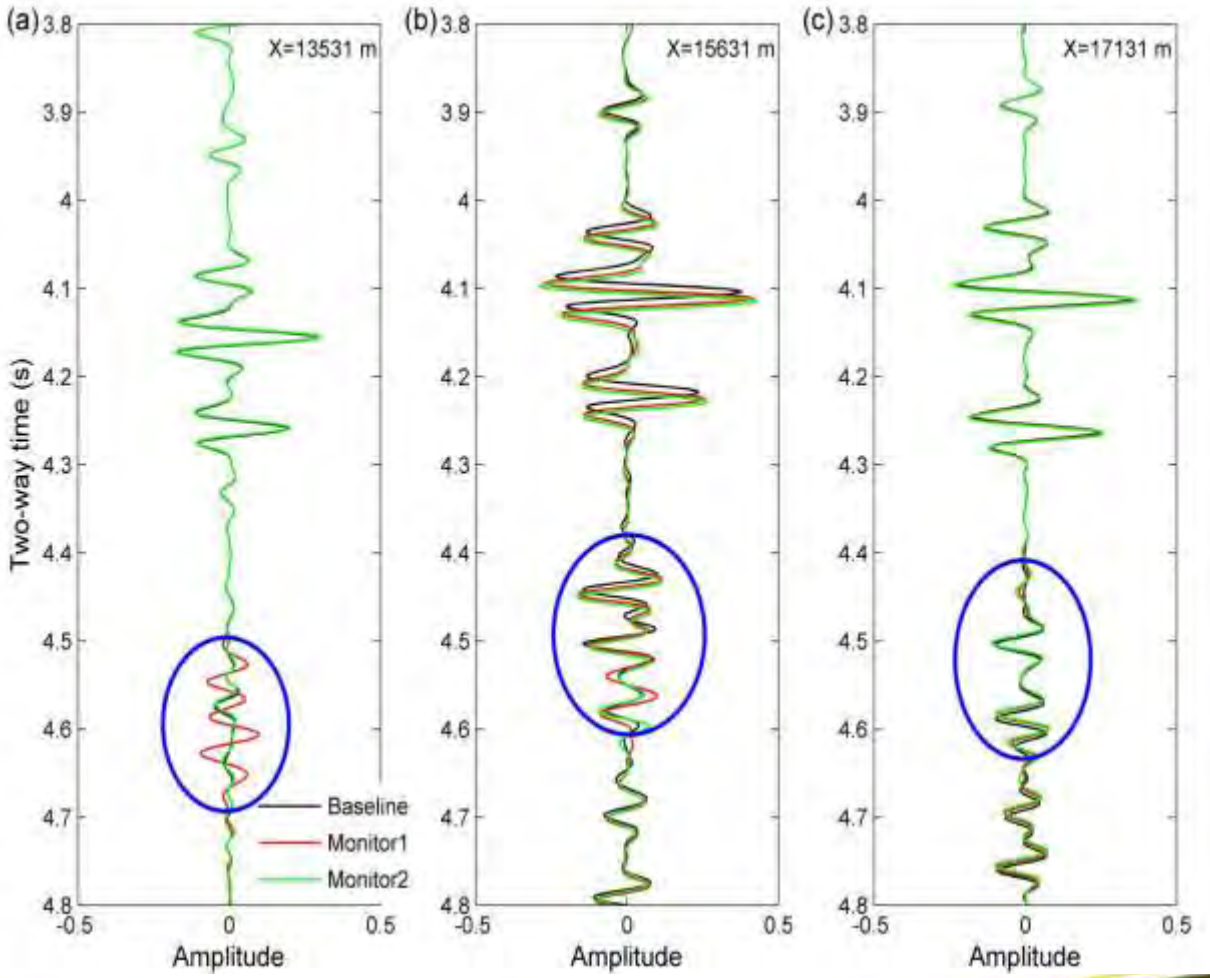
- Change in:
  - Saturation
  - Pressure/stress
  - Mechanical properties



P-wave velocity change for true earth model

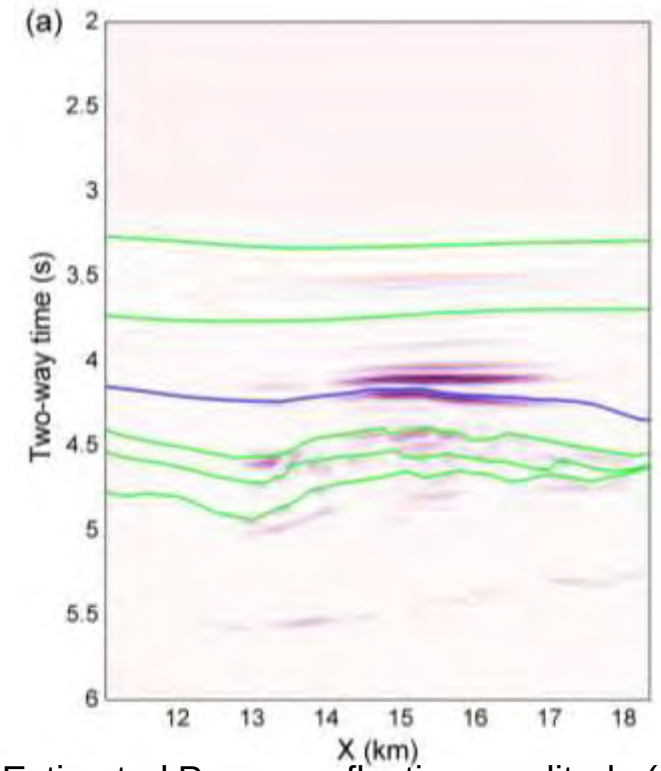
Time-lapse or 4D seismic

- What is measured:
  - Time differences
  - Amplitude differences
  - *“Devil is in the detail”*

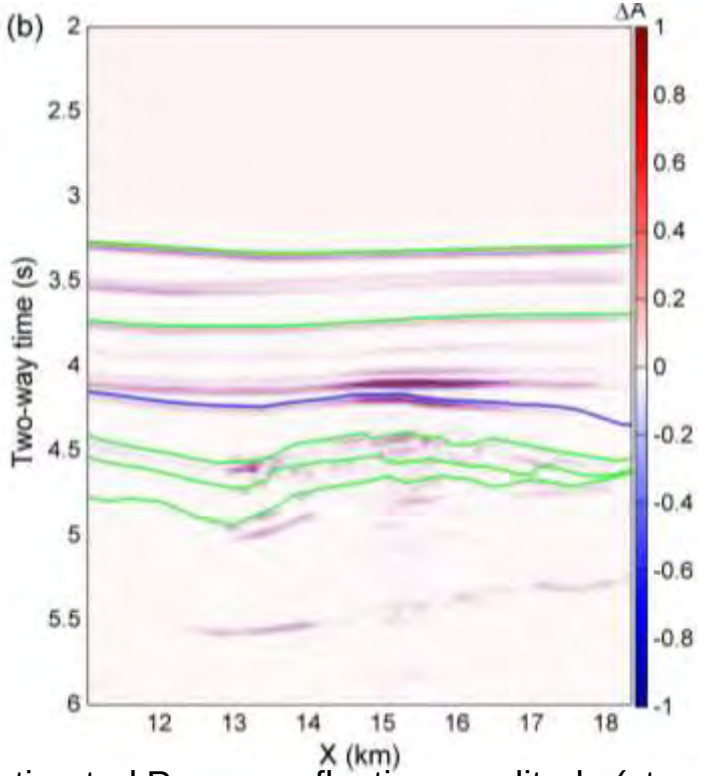


Time-lapse or 4D seismic

- Extract time-lapse amplitude changes



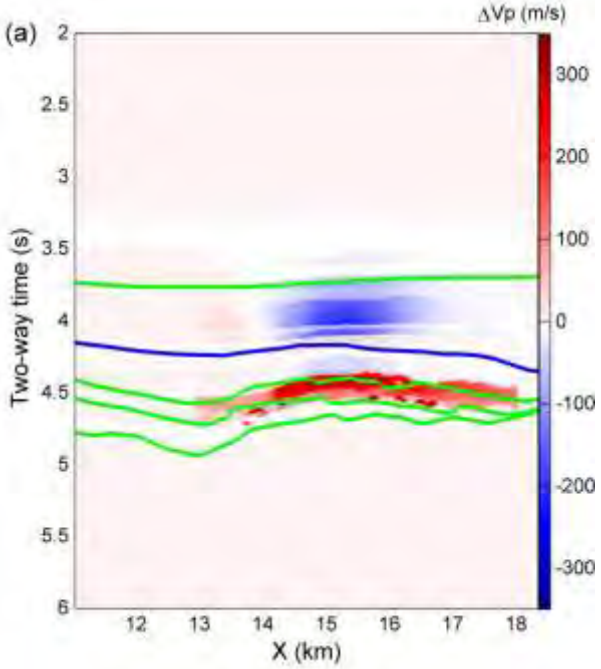
Estimated P-wave reflection amplitude (strength) changes using full-offset seismic data



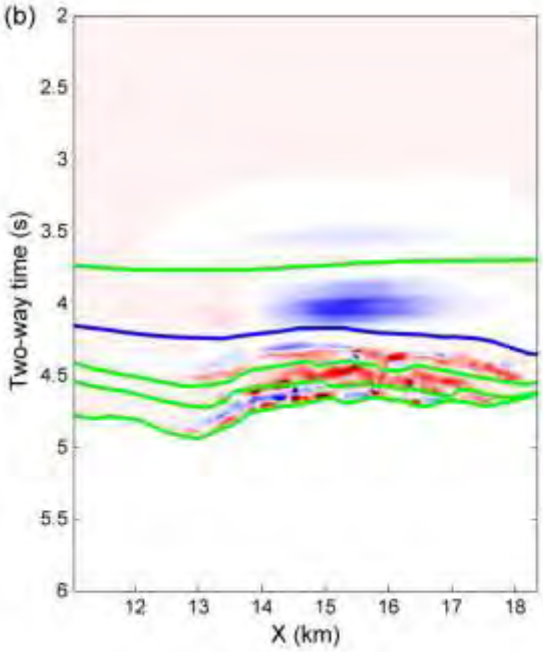
Estimated P-wave reflection amplitude (strength) changes using near-offset seismic data

Time-lapse or 4D seismic

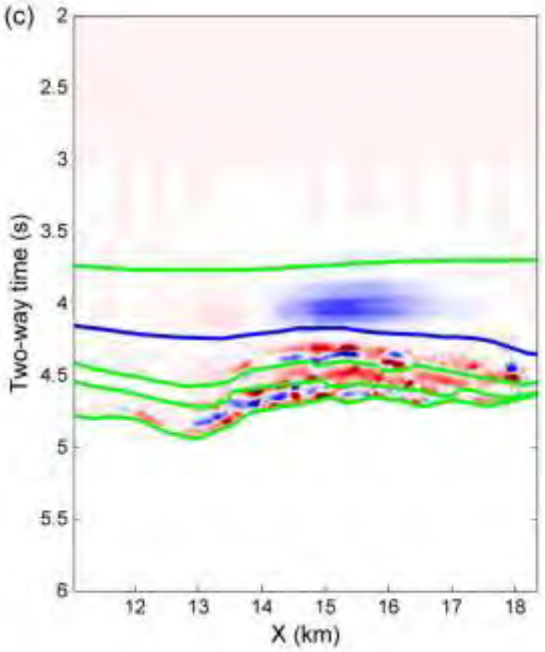
- Extract time-lapse velocity changes



P-wave velocity change for true earth model



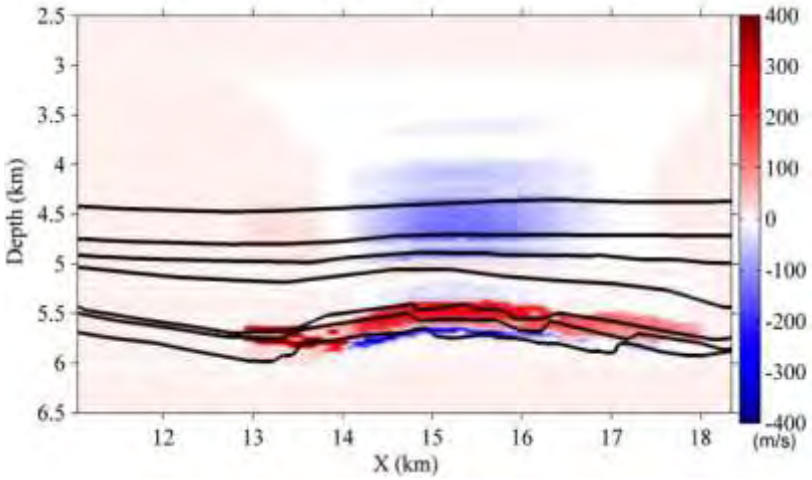
Estimated P-wave velocity change using full-offset seismic data

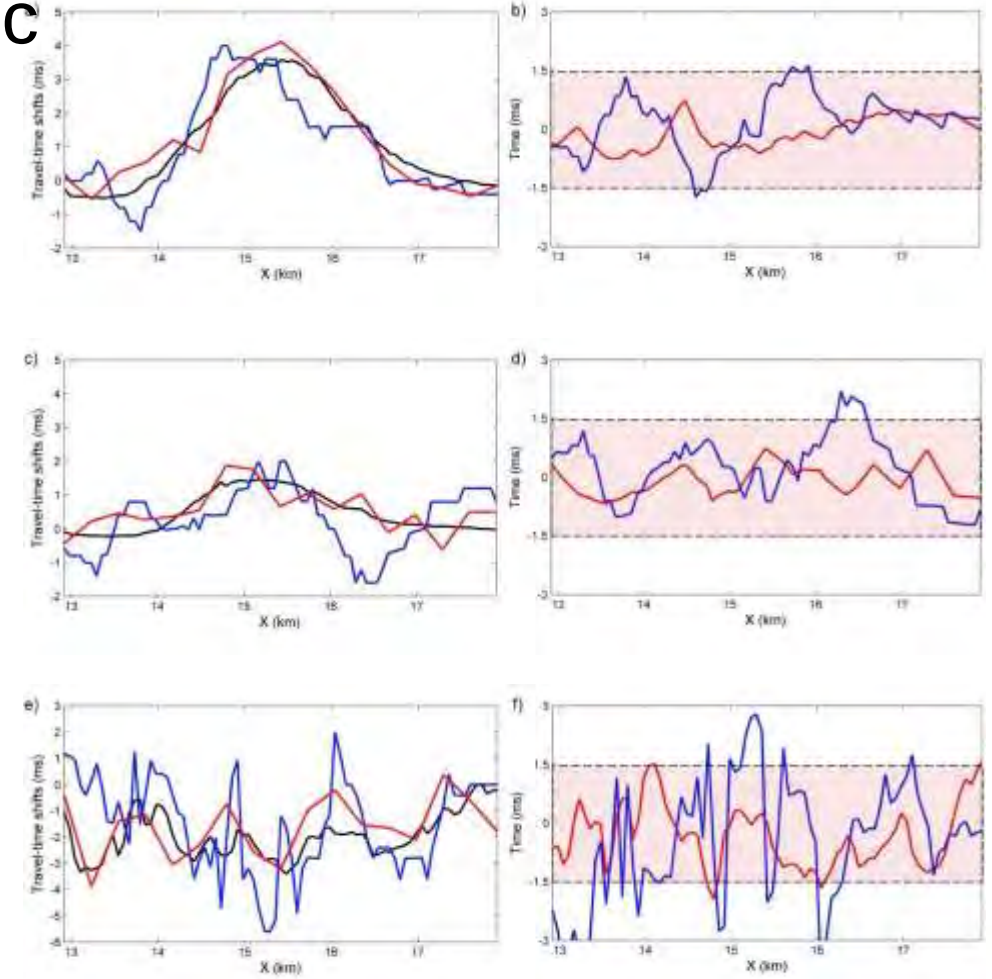


Estimated P-wave velocity change using near-offset seismic data

Time-lapse or 4D seismic

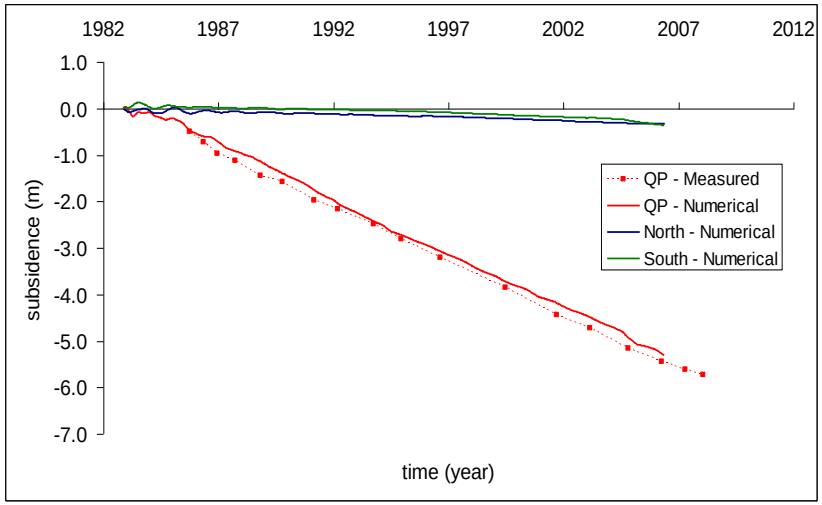
- Tau-p pre-stack approach

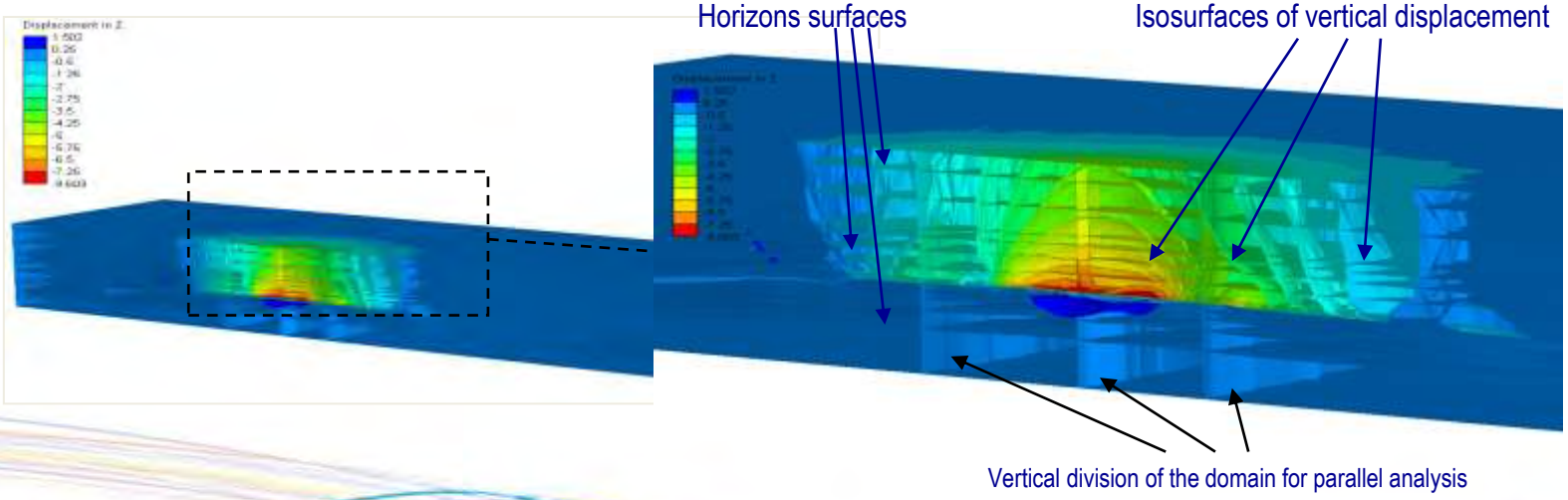




Vertical displacements predicted vs measured

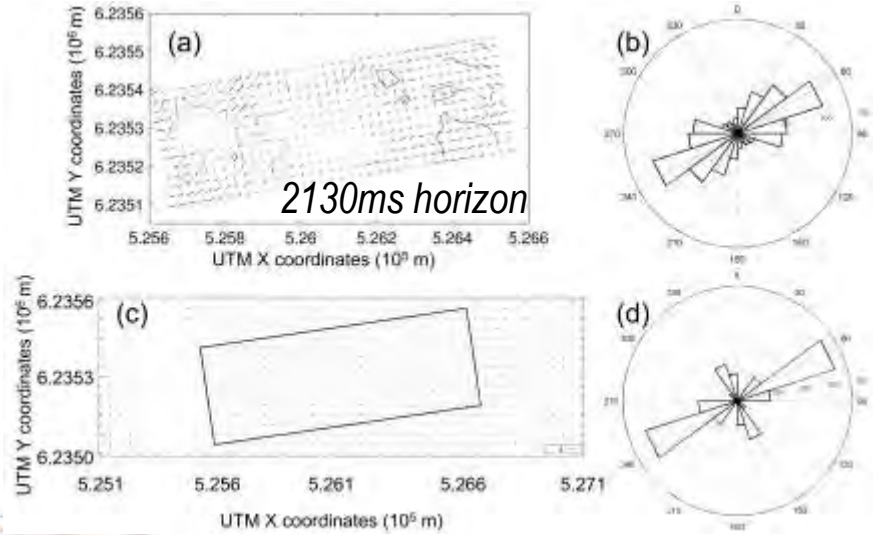
- Subsidence evolution recorded at seafloor
- From PO-035105 document
  - QP (524204,6237070)
  - North (522181,6242020)
  - South (527011,6231800)

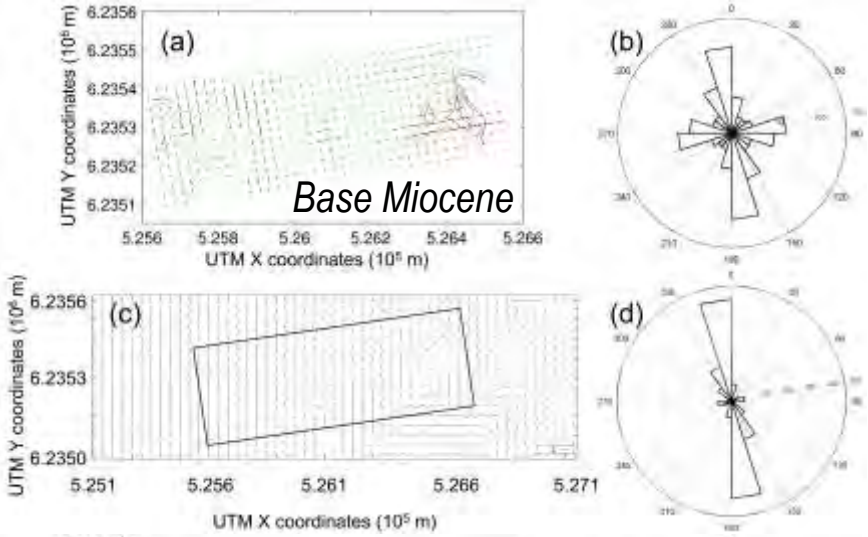


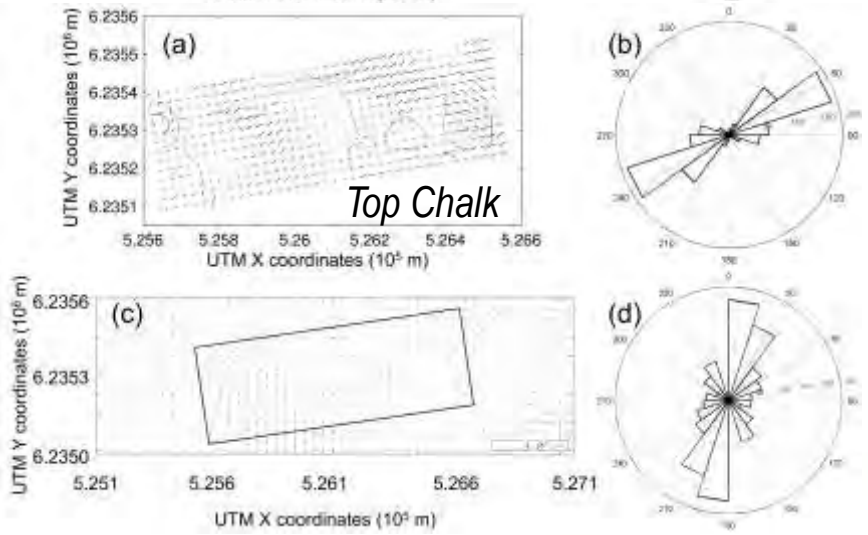


AVOA modelling

- Map reflection coefficients and fast P-wave direction
  - Using layer-matrix approach
  - Elasticity between chosen layers



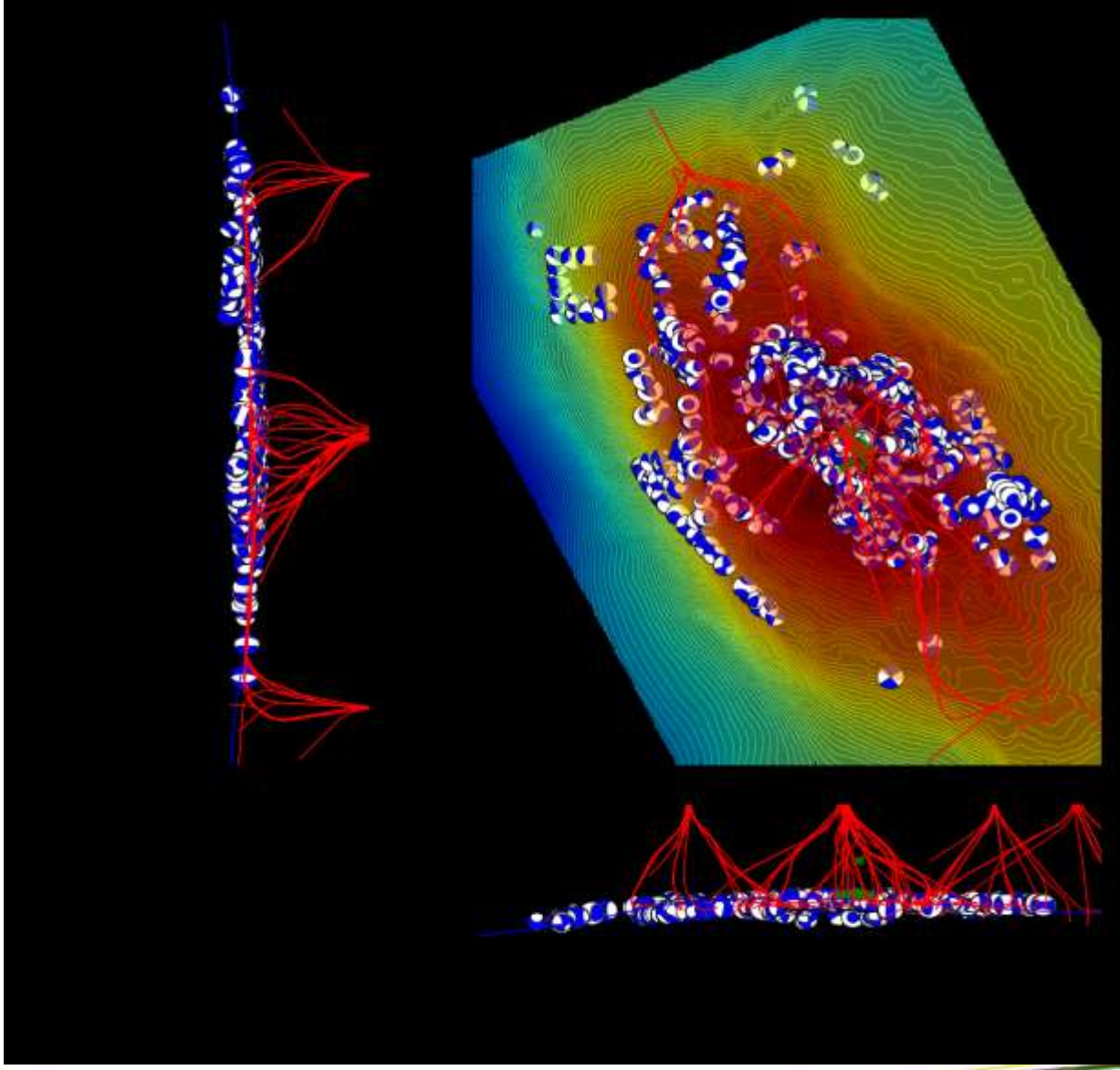




energy

Microseismicity:

- Valhall reservoir
- Geomechanics and microseismicity



Recap

- Likely not all CCS sites will be like Sleipner
- Large scale projects:
  - Not always ideal porosity/permeability
  - Injection rates and volumes
  - Fluid-rock (e.g., geochemical) alterations
- Must be capable of monitoring strains and overburden effects
  - Monitor seal integrity
  - Evaluate CO_2 containment

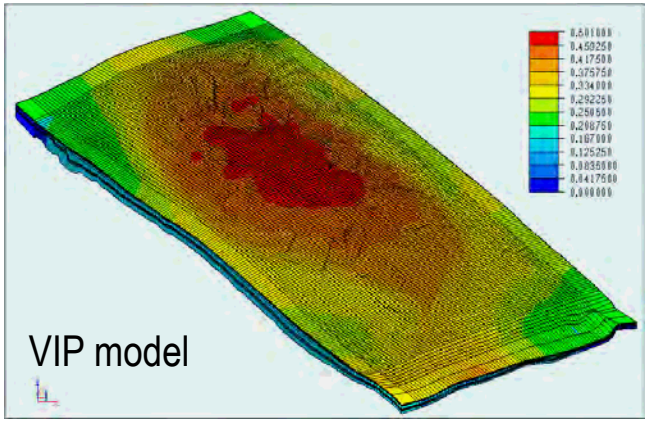
Challenges, uncertainties & way forward

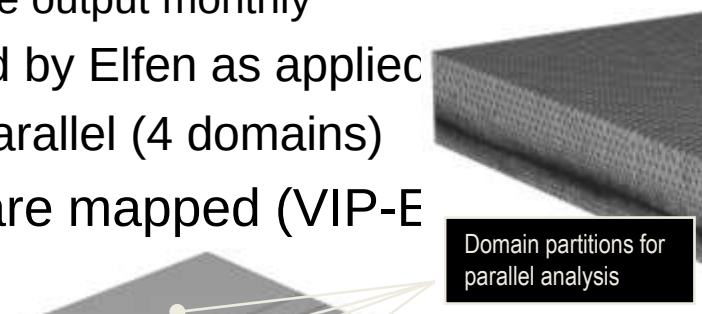
- Rock physics transforms
  - Models for multiphase fluids, patchy saturation, attenuation, anisotropy, plasticity
  - More data (e.g., shallower depths – overburden)
  - Calibration with in-situ data (not only core samples)
  - Scaling (static measurements to dynamic measurements) – significant knowledge gaps, but can apply site specific empirical relationships
- Hydro-mechanical models:
  - Calibration/history match fluid-flow and geomechanical simulation models
  - Systematic approach to model building (i.e. geometry & meshing)
  - Constitutive models from rock and petro-physics with up-scaling
  - Uncertainty of model parameters and geophysical/seismic attributes

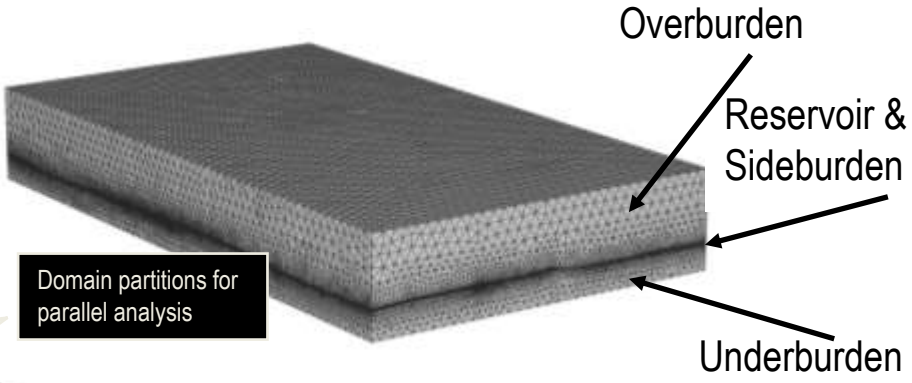
Energy
Leeds

Valhall reservoir, North Sea

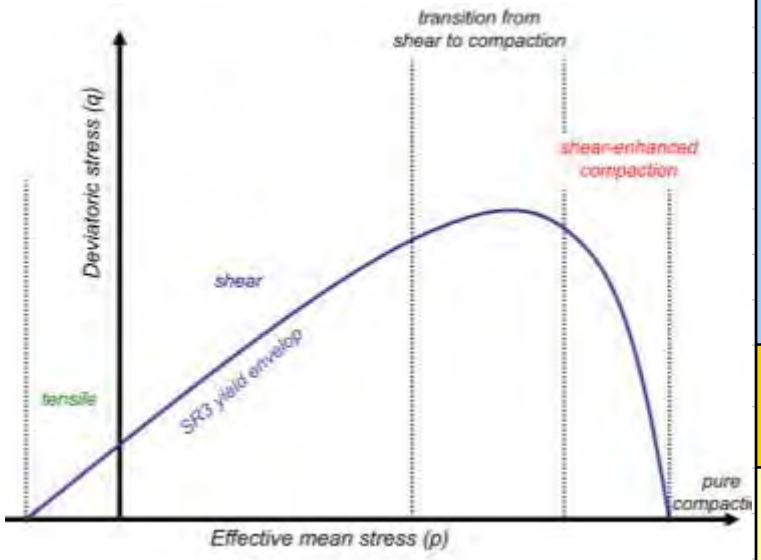
- ELFEN-VIP one-way coupling
  - Hexahedra mesh (6 million elements)
  - Cap plasticity, non-associated flow rule, water weakening SR3 adjusted to Valhall model (ISAMGEO PO-035105)
  - Soft coupled to 500,000 grid VIP model
  - VIP pore pressure output monthly
- Pore pressure used by Elfen as applied
- ELFEN solved in parallel (4 domains)
- 3 element groups are mapped (VIP-E
  - Reservoir Tor
  - Reservoir Hod
  - Reservoir faults







Elastic/Elasto-plastic properties

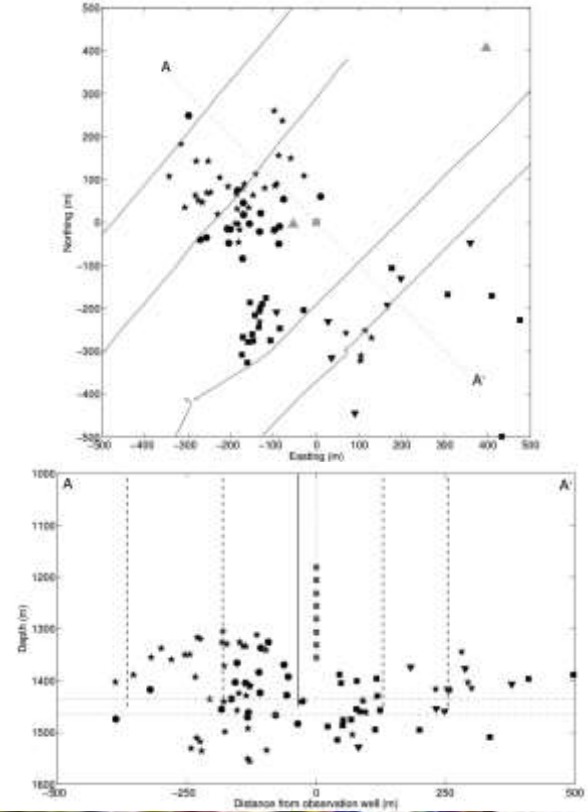


		Layer	E_x	E_y	E_z	ν_{xy}	ν_{yz}	ν_{zx}	G_{xy}	G_{yz}	G_{zx}	
			E_1 (MPa)		E_2 (MPa)	ν_1	ν_2		$G_1 = \frac{E_1}{2(1+\nu_1)}$ (MPa)	G_2 (MPa)		
OVERBURDEN	1	T200	240		150	0.25	0.15		96	55		Elastic
	2	T180	300		180	0.25	0.15		120	66		
	3	Intra mid Miocene	400		240	0.25	0.15		160	88		
	4	T110	500		300	0.25	0.15		200	110		
	5	Intra late Oligocene	650		390	0.25	0.15		260	130		
	6	Intra late Eocene	700		420	0.25	0.15		280	154		
	7	Early Eocene	750		450	0.25	0.15		300	165		
	8	—	=		=	=	=		=	=		
	9	Balder	2000		600	0.25	0.1		800	200		
	10	Sele	1100		900	0.3	0.2		423.0769231	360		
	11	Lista	1200		1000	0.3	0.2		461.5384615	360		
RESERVOIR & SIDEBURDEN	12 to 19	Tor	$E = 1000\phi^{-1.1}$			0.175			X			Elasto-plastic
	20 to 24	Hod										
UNDERBURDEN	26 to 27	Chalk	7000			0.17			X			Elastic
	28 to 29	Shale	7000		4000	0.2	0.1		2916.666667	1500		
	30	Shale	8000		6000	0.2	0.1		3333.333333	2500		
FAULTS	31 to 60	Reservoir	$E = 900\phi^{-1.1}$			0.25			X			Elasto-plastic
	61 to 90	Overburden	300			0.3			X			Elastic

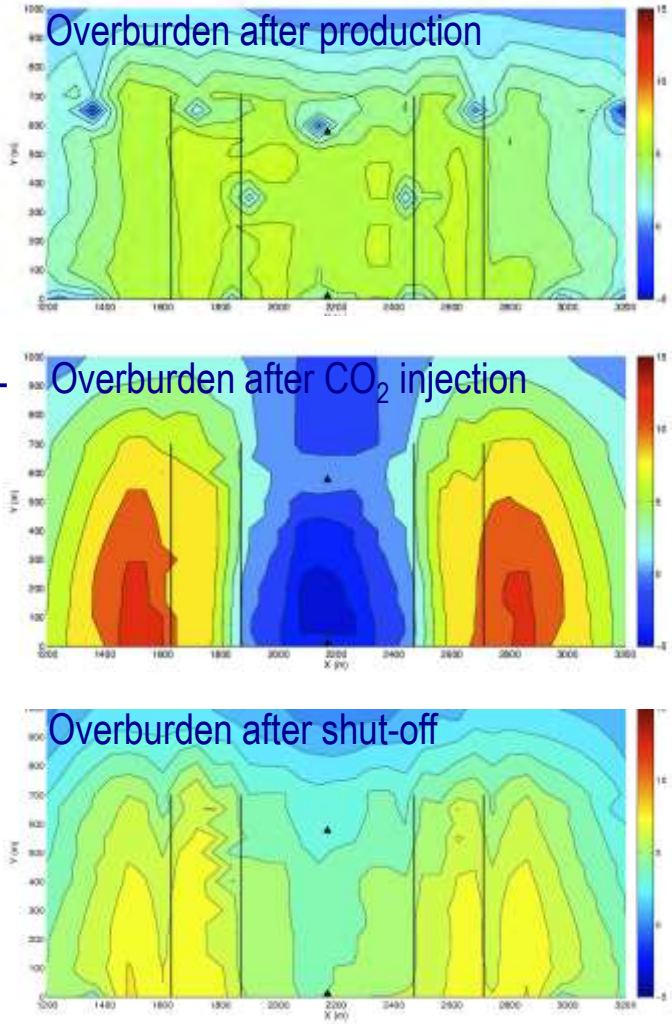
Microseismicity:

- Weyburn CCS pilot
- Geomechanics and microseismicity

Microseismic locations



Overburden fracture potential



energy