Computational geomechanics applications etc.

EPFL

GeoEnergyLab

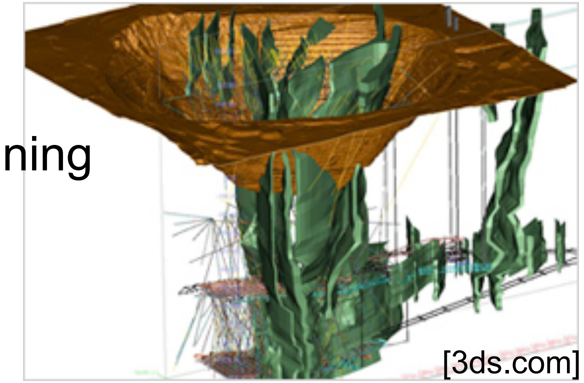
What we did not cover

- Other multi-physics coupling, notably:
  - Thermo-poro-elasticity (THM)
    - Thermal pressurization (heat induced pp increase), heat conduction / convection (hydro-thermal problems) …
    - Note that mechanics do not influence thermal effects (TH->M, but no M->T)
  - Chemo-poro…
    - Most of the time chemical reactions→ change in mechanical respons: C-> M (not M-> C)
    - Notable exception: pressure solution
- Dynamics
  - Dynamic liquefaction, waves and poroelasticity (squirt flow) etc.
- Material rate dependent effects
  - Viscoplasticity etc.
- Fracture growth

Natural hazards

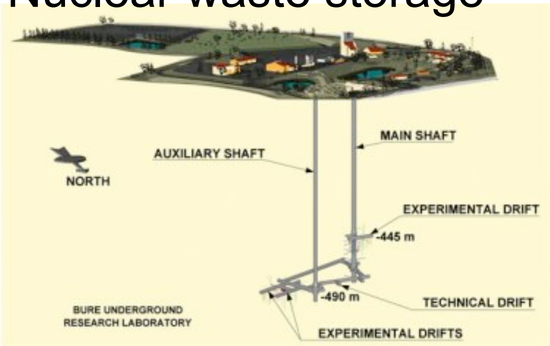
[blogs.agu.org/landslideblog/]

Mining



[3ds.com]

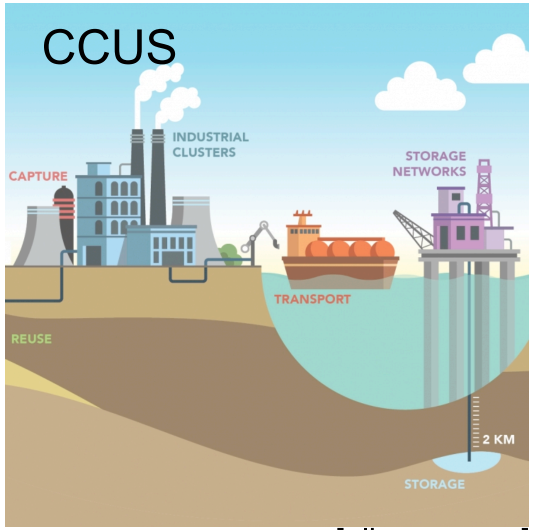
Nuclear waste storage



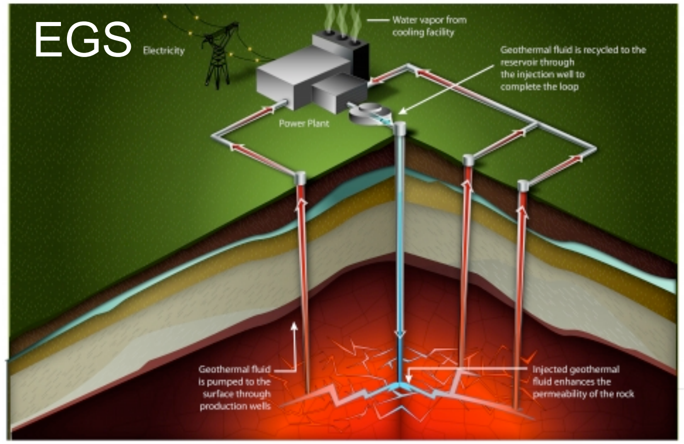
[ANDRA]

Oil & Gas

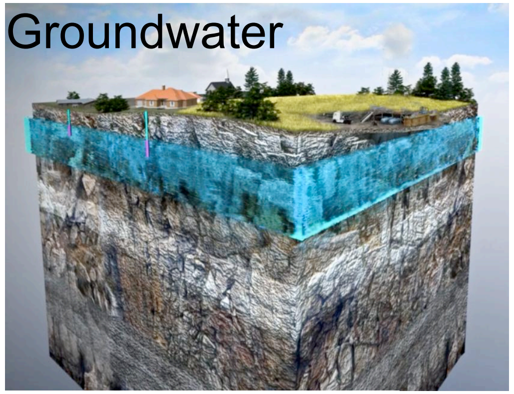
[pubs.spe.org/en/jpt]



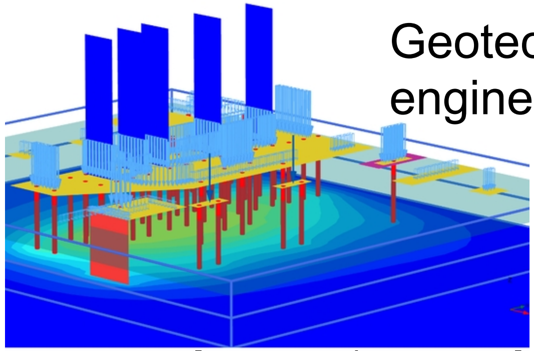
[alignccus.eu]



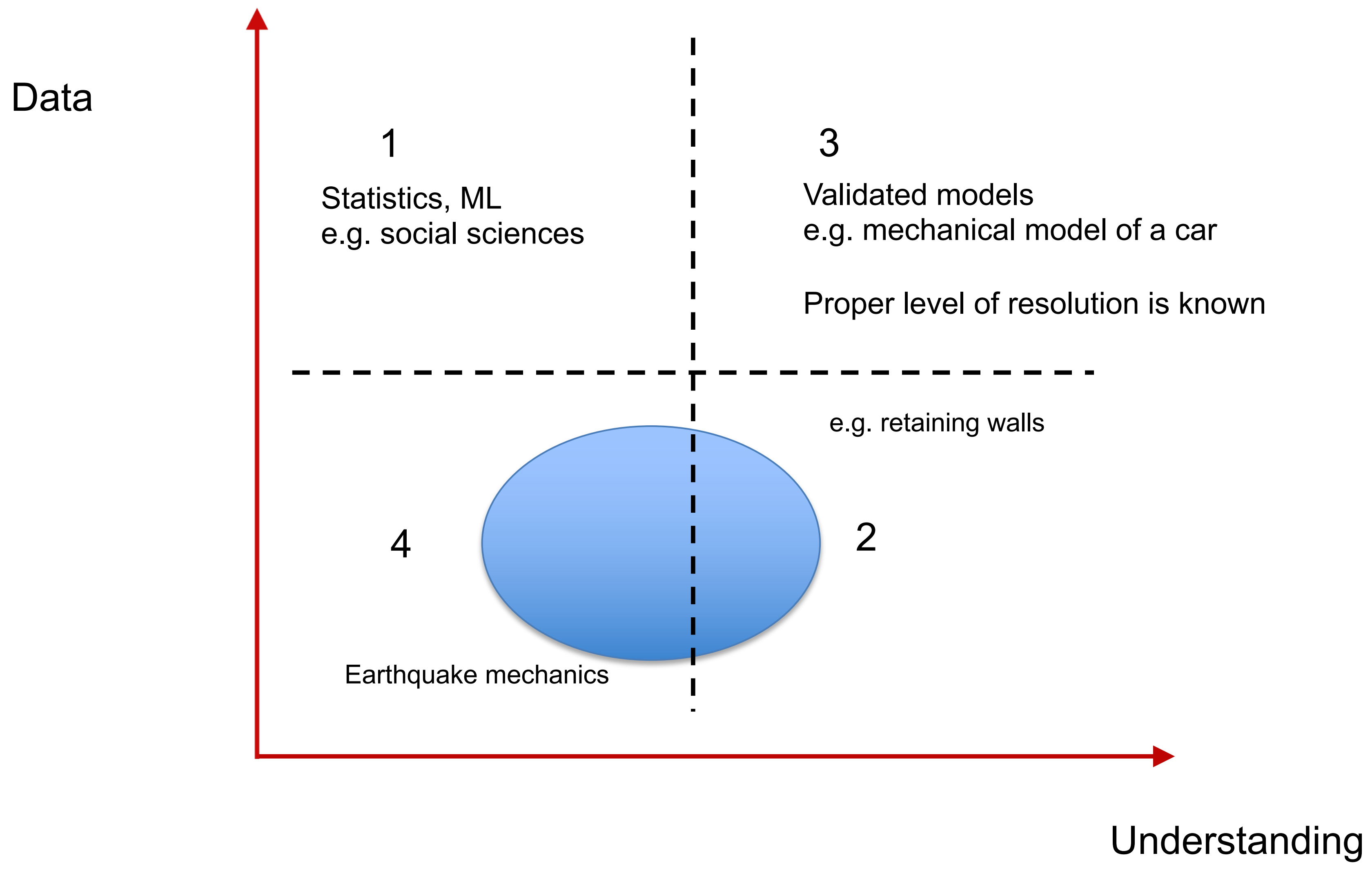
[DOE, Geothermal Technologies Program]



Geotechnical engineering



[cmwgeosciences.com]


Data
1
Statistics, ML
e.g. social sciences
3
Validated models
e.g. mechanical model of a car
Proper level of resolution is known
e.g. retaining walls
4
2
Earthquake mechanics
Understanding

Model verification vs validation

- Verification
  - Ensure that the numerical tool **correctly/accurately** solve the equations it is supposed to solve
    - E.g. check a FEM elastic model against Boussinesq analytical solution for a circularly loaded area
    - Same for more complex equations: -> benchmarking between different numerical codes.

- Validation
  - Ensure that the numerical model **correctly/accurately** reproduce the physical phenomena observed
    - E.g. comparison between the prediction of a model and a lab experiment WITHOUT FITTING the model parameters
    - E.g comparison between the prediction of a model and a field experiment, allowing a reasonable adjustment of the model parameters

- Validation without verification is the road to disaster

Modeling in geomechanics

- " A model is a simplification of reality rather than an imitation of reality. It is an intellectual tool that has to be designed or chosen for a specific task."
- "The design of a model should be driven by the questions that the model is supposed to answer rather than the details of the system that is being modelled"
  - Over-complexification of models do not lead to better predictability
- "… appropriate to build a few very simple models rather than one complex model; the simple models would either relate to different aspects of the problem, or else address the same questions from different perspectives"
- "Instead of trying to validate a model, one should aim at gaining confidence in it and modify it as data arrives. "
- "Purpose of modeling data limited problems is to gain confidence and explore potential trade-offs and alternative, rather than to make absolute predictions"

[Starfield & Cundall, 1998 – towards a methodology for rock mechanics modeling]

In practice

- Why modeling ? What is/are the question/s ?
- Use a model early – do not delay until receiving field data
- Look at the mechanics of the problem – perform dimensional analysis and scaling
- Think of an experiment to decipher between possible mechanisms – this can be numerical experiments
- Start simple, and complexify only when required (when the simple model is invalidated)
- If the model has weaknesses that can not be remedy, make a series of simulations to bracket the true case
- Once simple models have been mastered, complexify slowly to investigate the effects previously neglected

"There is a dialectic between geological detail and engineering understanding"

Commercial Tools

- Itasca C.G.
  - FLAC 2D / 3D (THM) – explicit FV code – shine for very non-linear problems (elastoplastic)
  - DEM codes: Udec, PFC …
  - Mining, nuclear waste, O&G

- Plaxis
  - 2D/3D – (T)(H)M – elasto-plastic
  - Geotech.
- RS2/RS3 (RocScience)
  - FE (H)M - elasto plastic

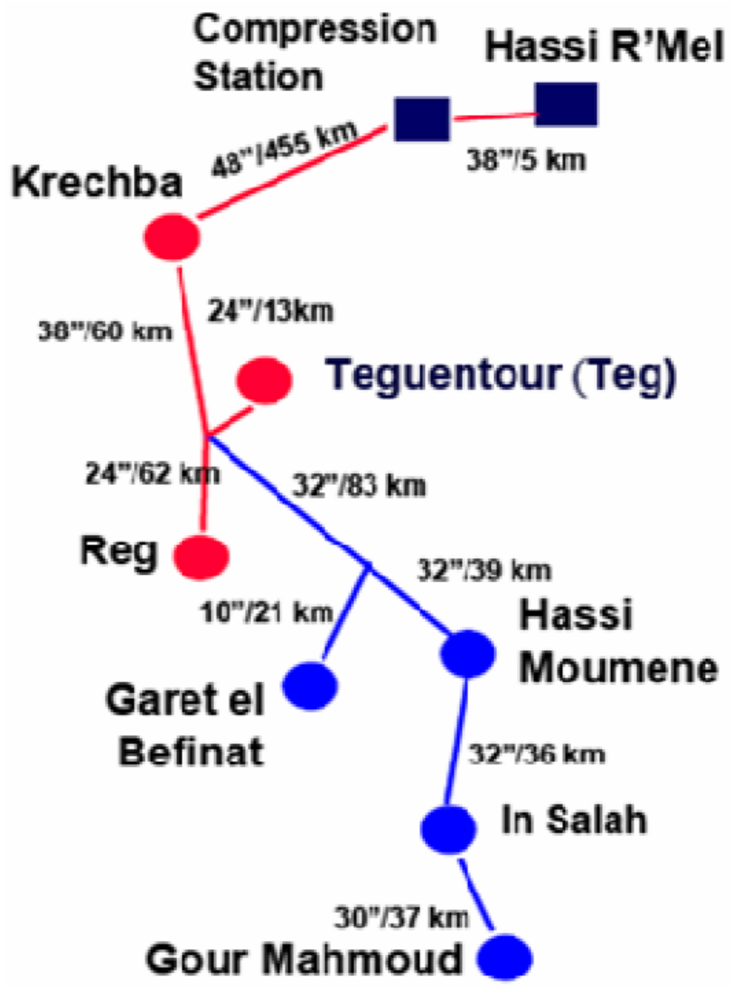
- Optum
  - G2/G3 – (H)M – elasto-plastic, limit analysis

- ELFEN (RockField)

- Abaqus (DS), ANSYS

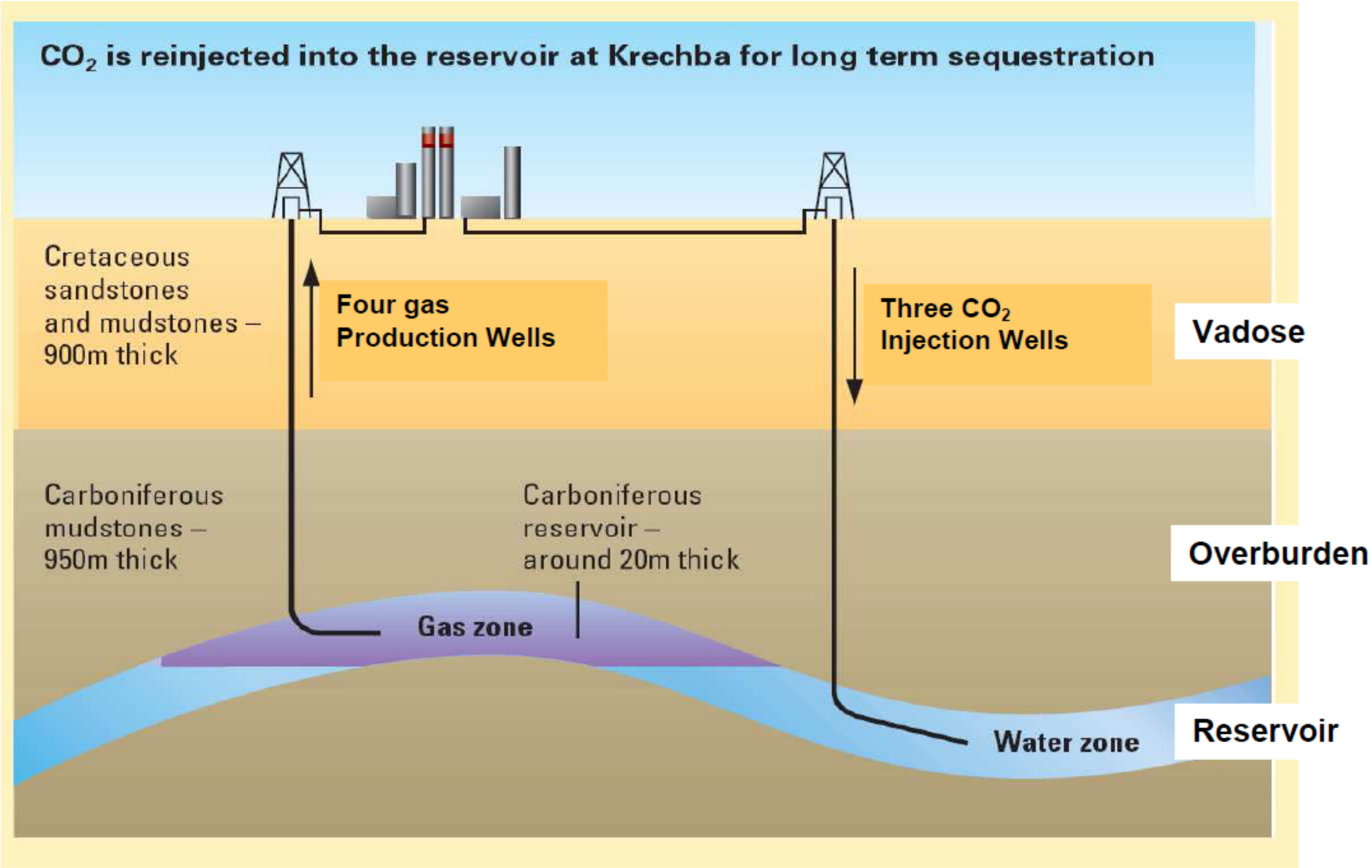
AN EXAMPLE

In Salah Gas (ISG) Project

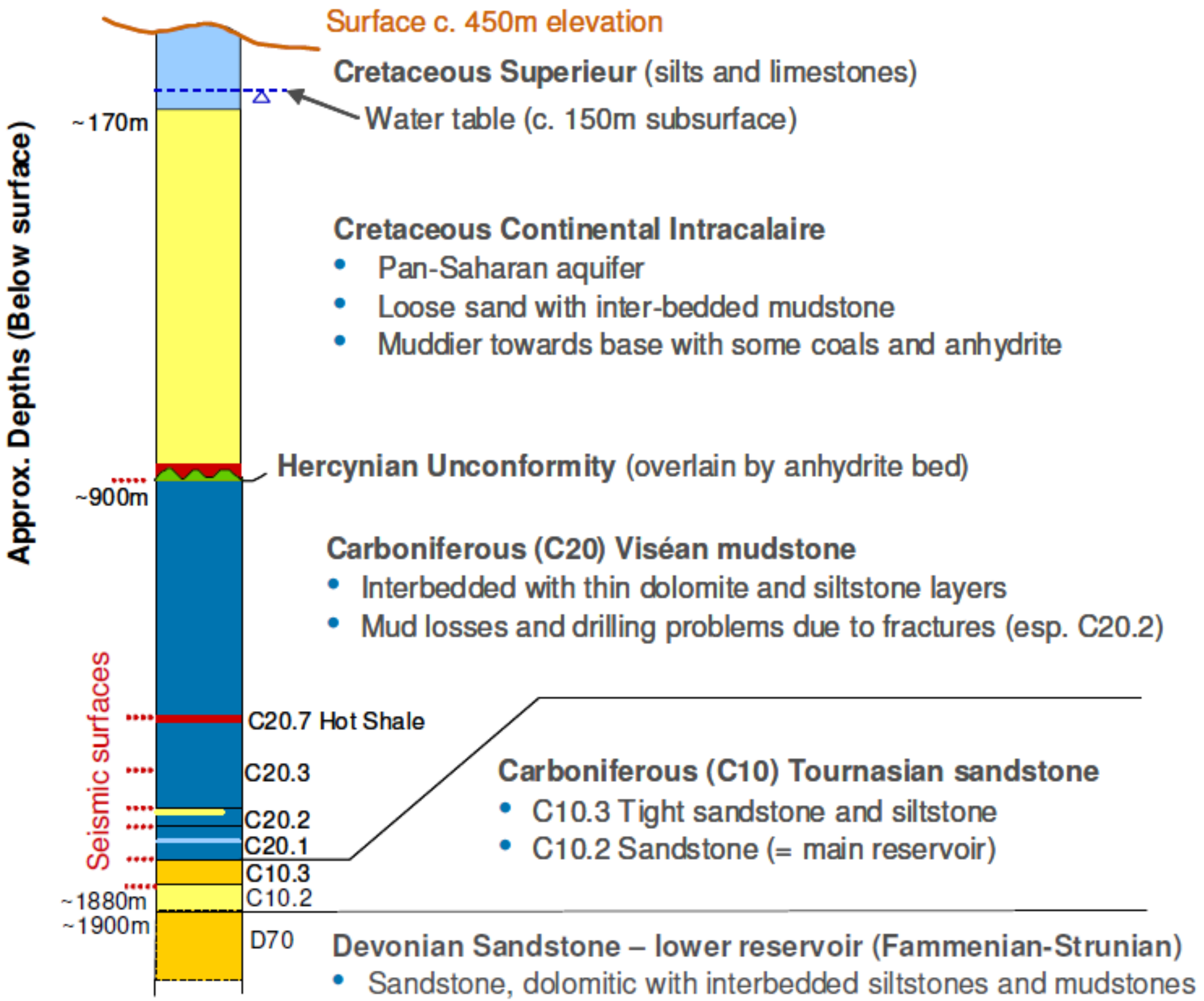


Schematic of ISG
(Phase 1 is shown in red; phase 2 in blue)

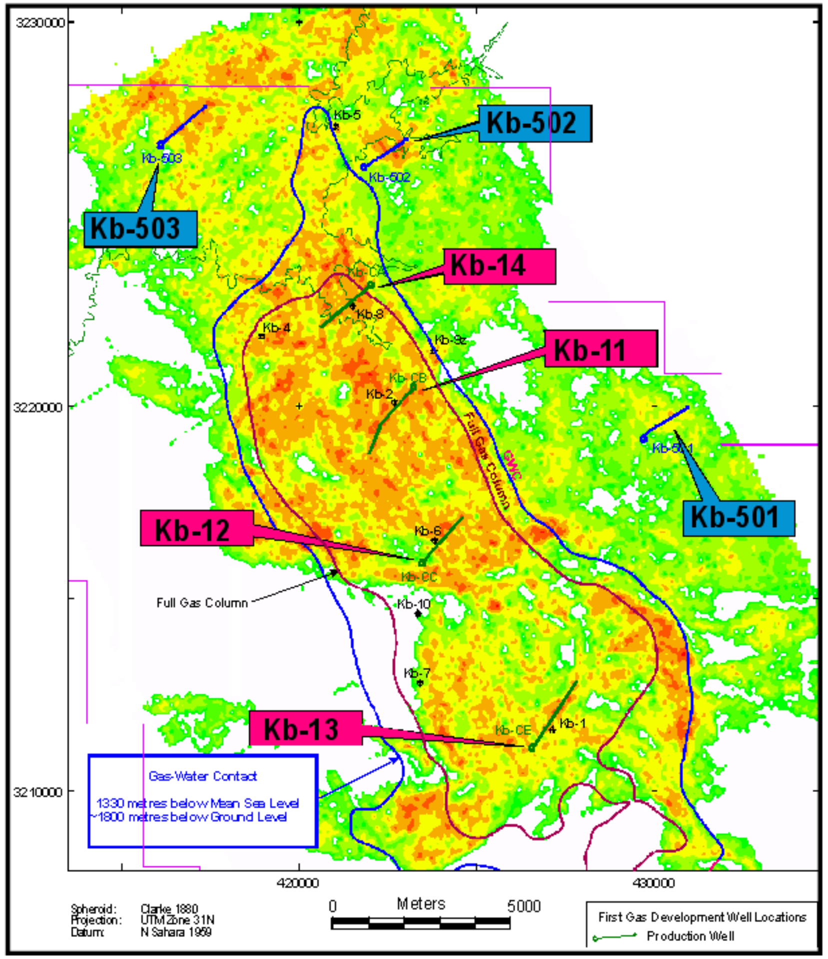
ISG Schematics

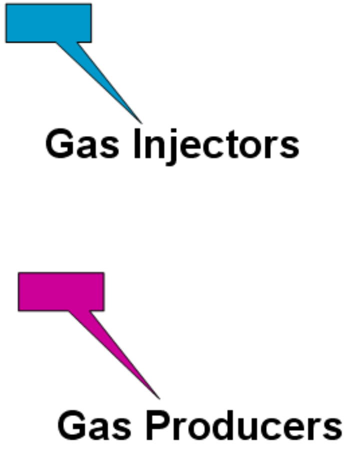


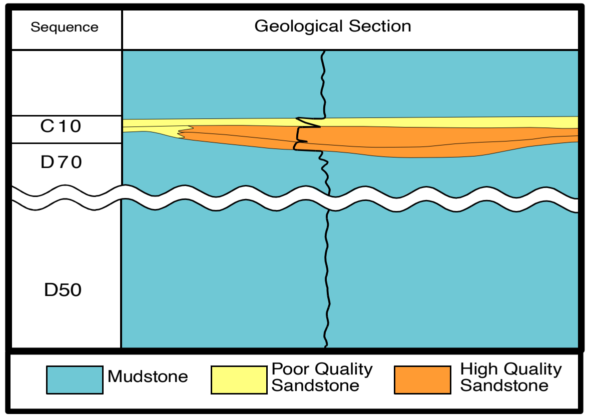
Krechba Stratigraphic Structure



The In Salah Field Layout







C10.2 Reservoir Quality

- **Avg. porosities range 13 – 20%**
- **Permeability highly variable - average around 10 mD**

Background

- Krechba is currently described as a fractured and faulted field.
- Fracture:

  Open fracture network along NW-SE.

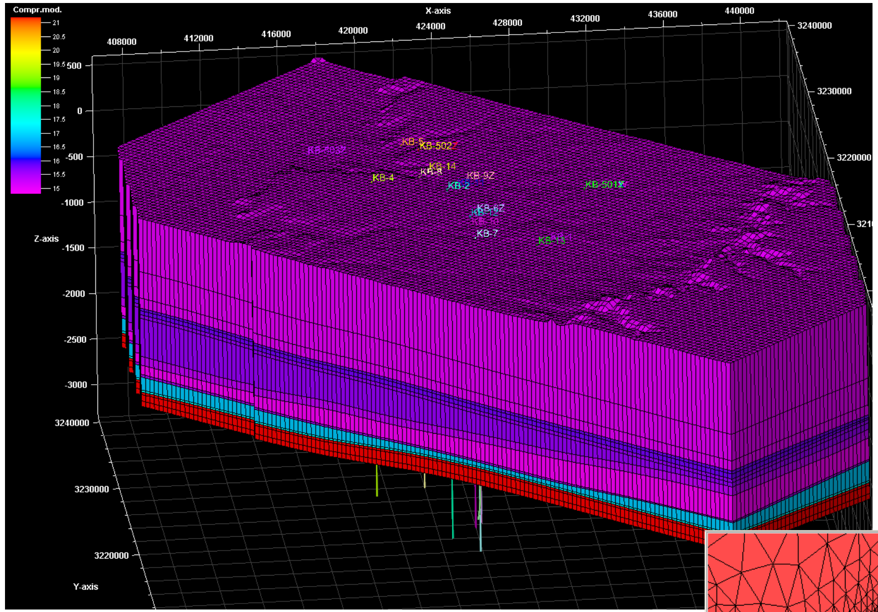
  Extended to ~1000m TVDSS (lack of data elsewhere).
- Fault: Reverse type

  1 km long to 9 km long. Throw ranging from 10 m to 40 m.
- Only the fracture network is taken into account: fault is not yet taken into account in the geological model.
- The whole field is assumed to be fractured the same (density) as around the well (FMI study, see next).
- BorStress results:

  Stress ratio Q = 1.1, Sv is the intermediate principal stress. Strike-Slip regime

  AZ(SHmax) = 135 degree from North (NW-SE).

3D Geomechanical Model



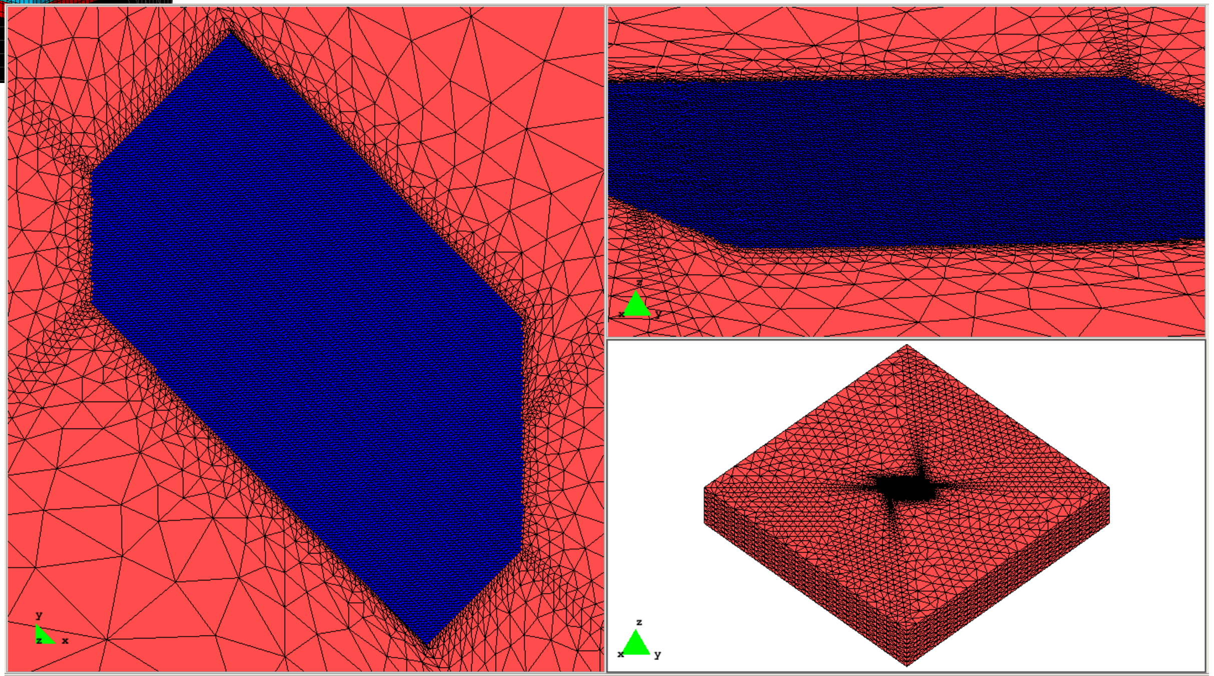
- Petrel model covers 36km by 50km
- Grid size in reservoir: 327m*289m*25m

- Embedded model used in Visage covers 285km by 285km
  1,128,191 elements and 195,757 nodes

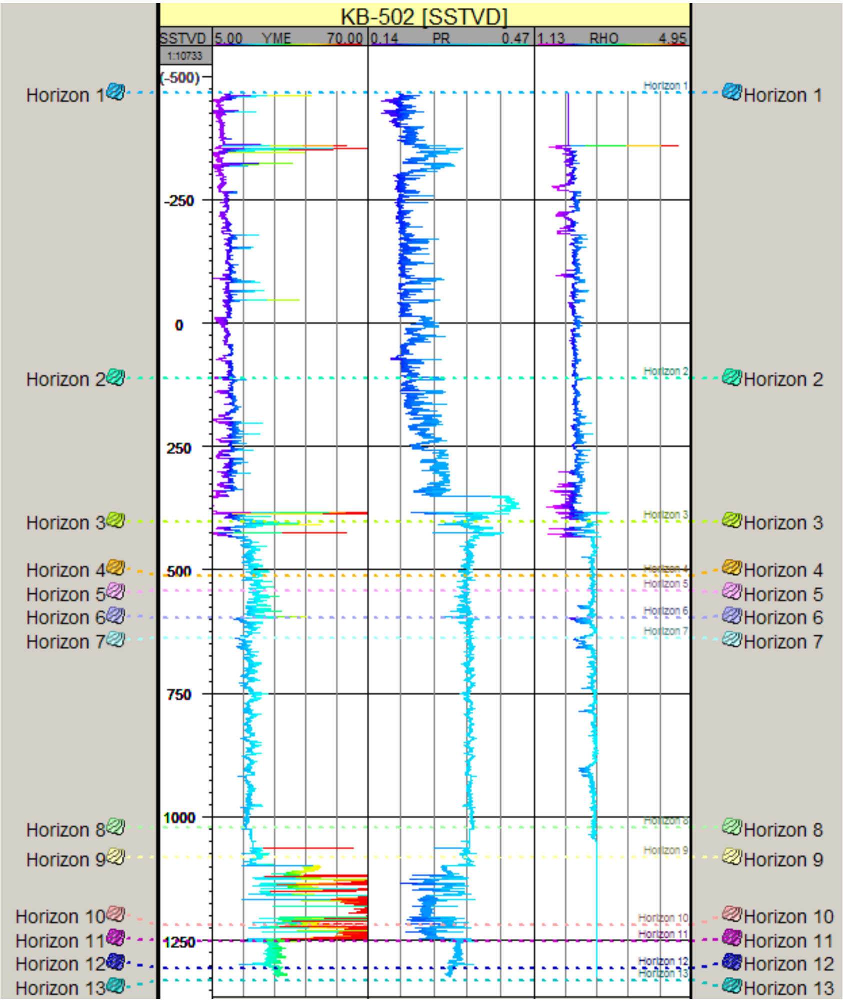
– Central part corresponds to the Petrel model

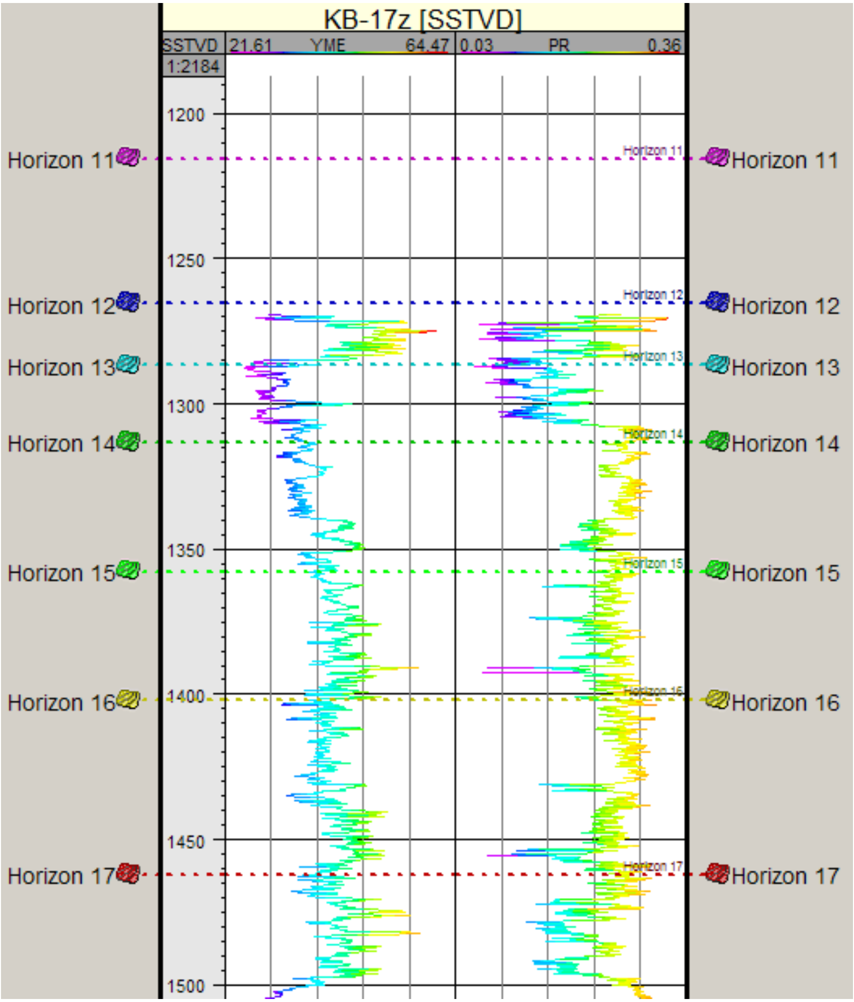
– Properties are constant per layer

– Embedding with unstructured tetrahedral mesh

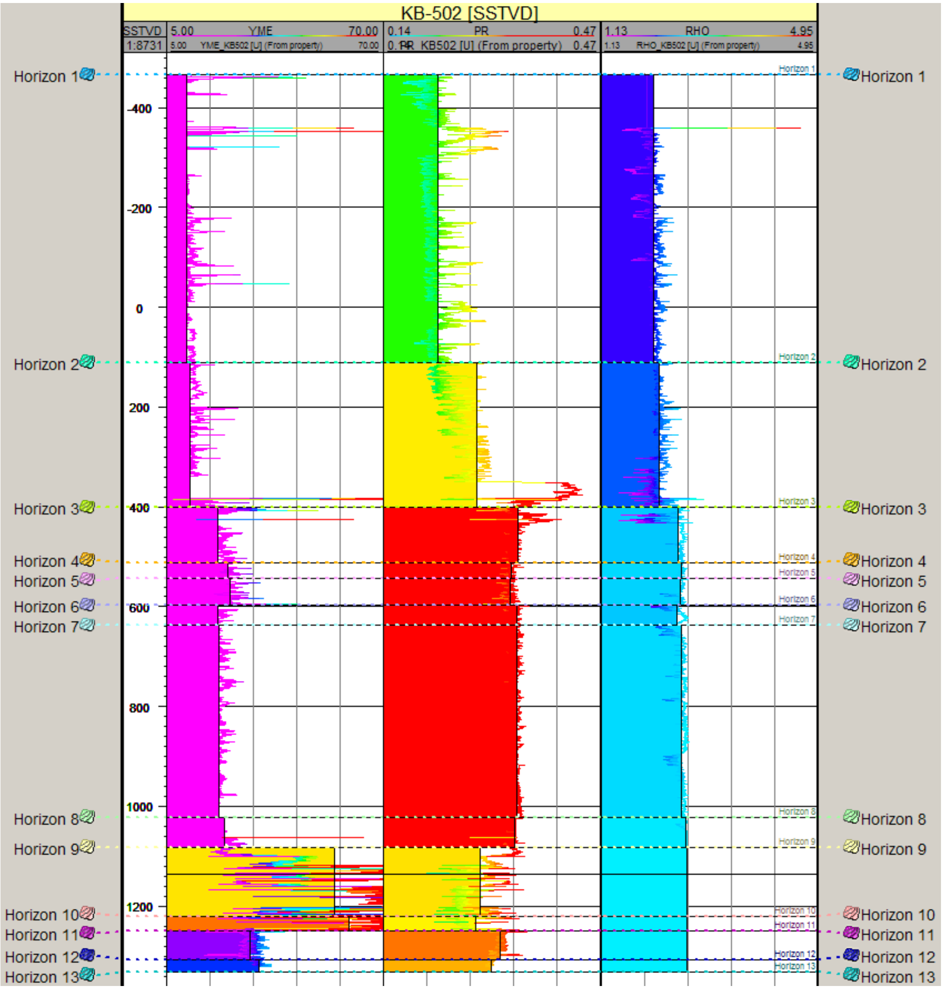


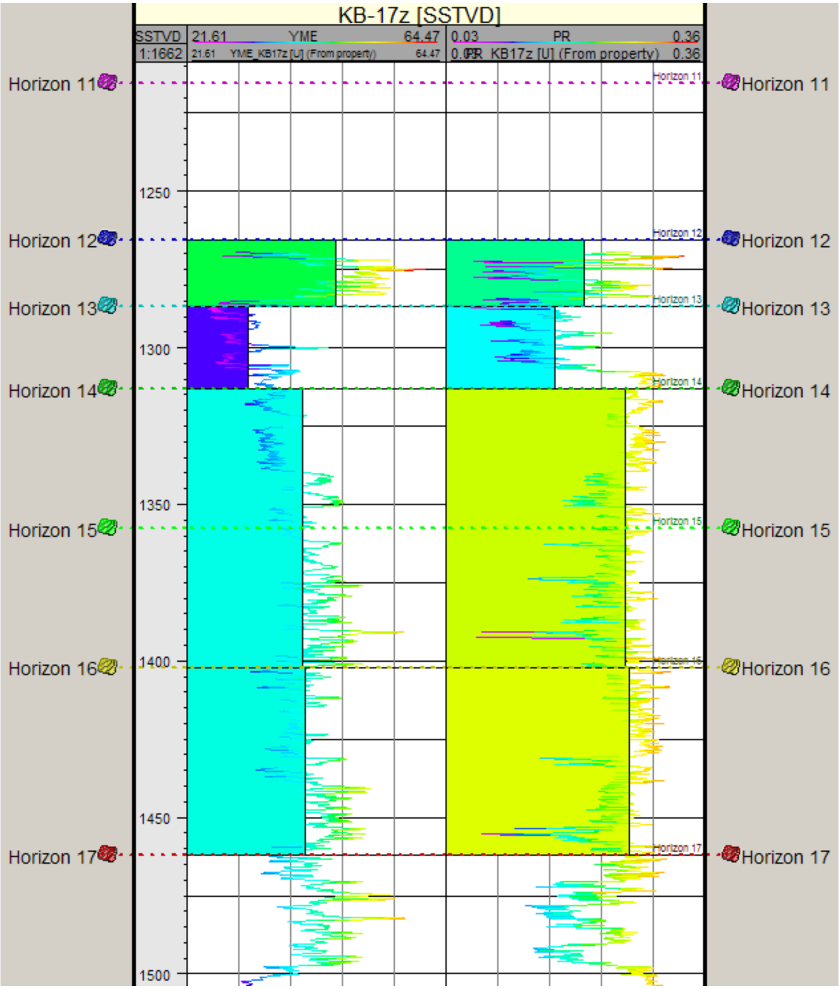
Rock Properties Upscaled from Sonic Logs





Rock Properties layer average from Sonic Logs

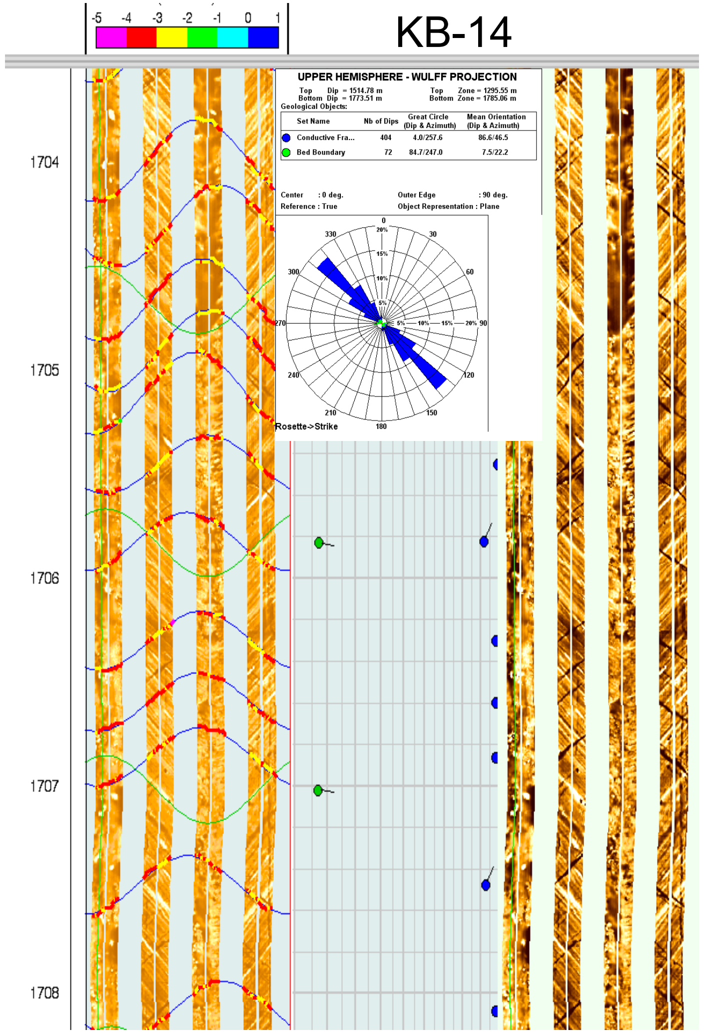


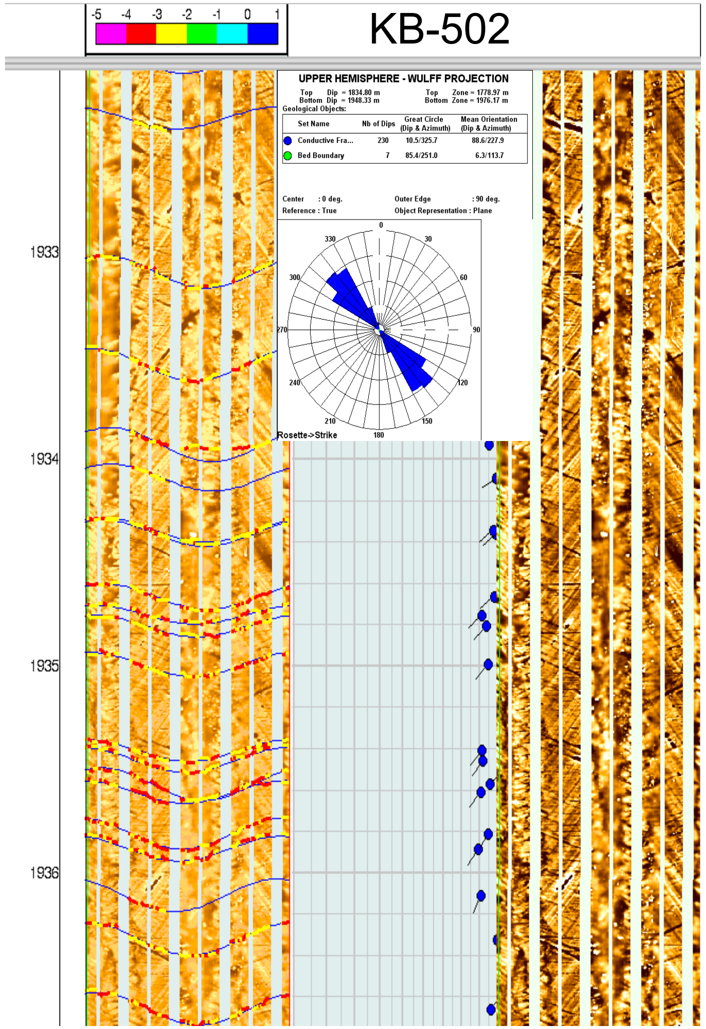


Layering and Intact Properties

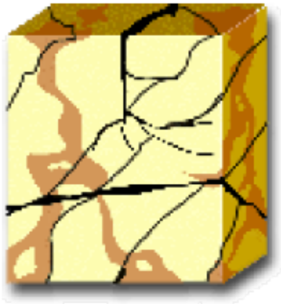
Description	Zone ID	Thickness (m)	YME (GPa)	PR	RHO (g/cc)	BIOT
Top (ground surface)	1	658	11.1	0.223	2.06	1
New Intermediate zone	2	290	11.9	0.283	2.16	1
New Intermediate zone	3	110	20.3	0.345	2.48	1
Hercynian Unconformity +40	4	27	23.5	0.336	2.55	1
Hercynian Unconformity	5	41	24.0	0.334	2.52	1
Hercynian Unconformity - 40	6	40	20.2	0.344	2.48	1
New Intermediate zone	7	306	20.6	0.345	2.56	1
End of Fracture	8	75	22.5	0.340	2.62	1
Hot Shale	9	161	30.0	0.290	2.65	1
New Intermediate zone	10	24	30.0	0.280	2.65	1
C20-2 (Cap Rock)	11	106	30.0	0.320	2.65	1
C10-3 (Tight Reservoir)	12	23	32.6	0.300	2.47	1
C10-2 (Injection zone)	13	27	32.0	0.300	2.51	1
Underburden (new)	14	45	40.0	0.257	2.51	1
Underburden (new)	15	45	40.0	0.257	2.51	1
Underburden (new)	16	60	40.0	0.257	2.51	1

Fracture Study





Effect of Fractures at grid scale



Estimate the Grid-scale (dual porosity medium) properties from:

- Matrix poroelastic properties (from sonic)
- Fractures properties (P32, compliances, orientation)

- Defect compliance tensor [Kachanov 1980, Sayers & Kachanov 1992 …]

$$\mathcal{H}_{ijkl} = P_{32}\left((B_N - B_T)n_i n_j n_k n_l + \frac{B_T}{4}(n_i n_l \delta_{jk} + n_i n_k \delta_{jl} + n_j n_l \delta_{ik} + n_j n_k \delta_{il})\right)$$

- Grid-scale Properties

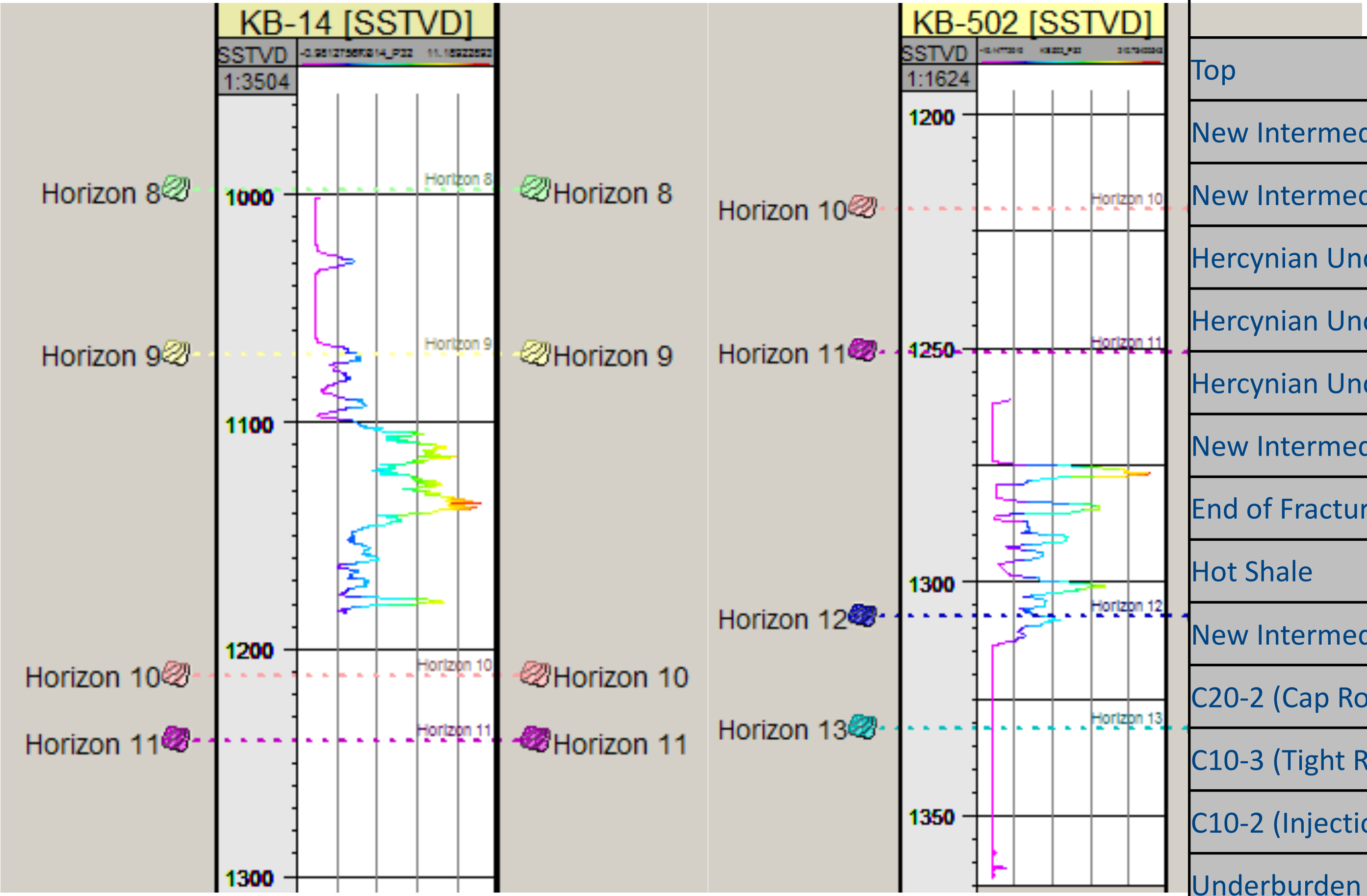
Elastic Compliance

$$\mathbf{M} = \mathbf{M}_m + \boldsymbol{\mathcal{H}}$$
$$\mathbf{L} = \mathbf{M}^{-1}$$

Biot's coefficients

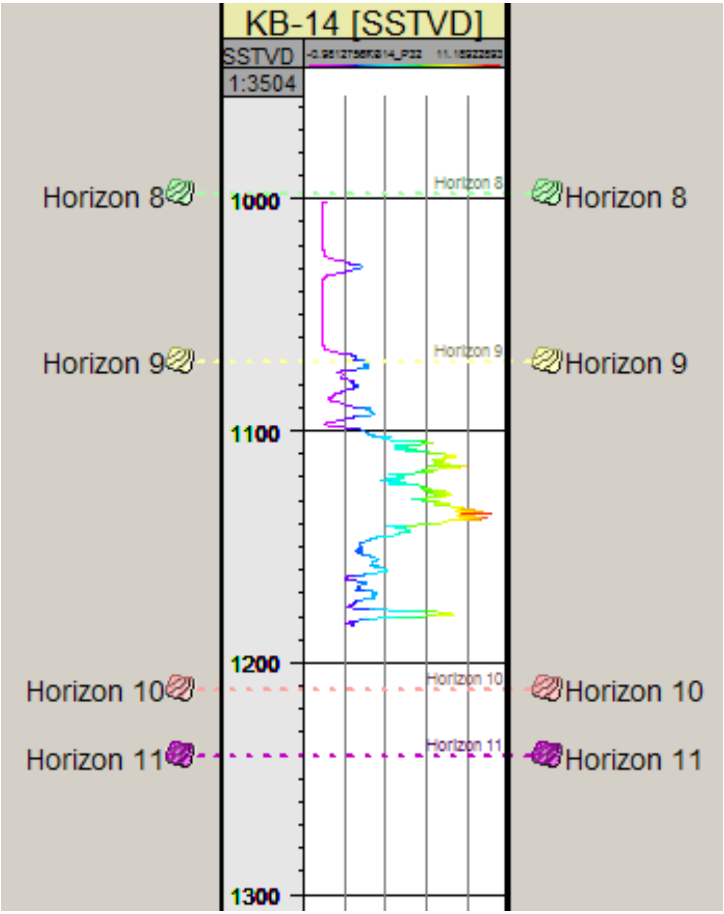
$$\boldsymbol{b}_M = \mathbf{L}\mathbf{M}_m \boldsymbol{I} b_m$$
$$\boldsymbol{b}_F = \mathbf{L}\boldsymbol{\mathcal{H}}\boldsymbol{I}$$

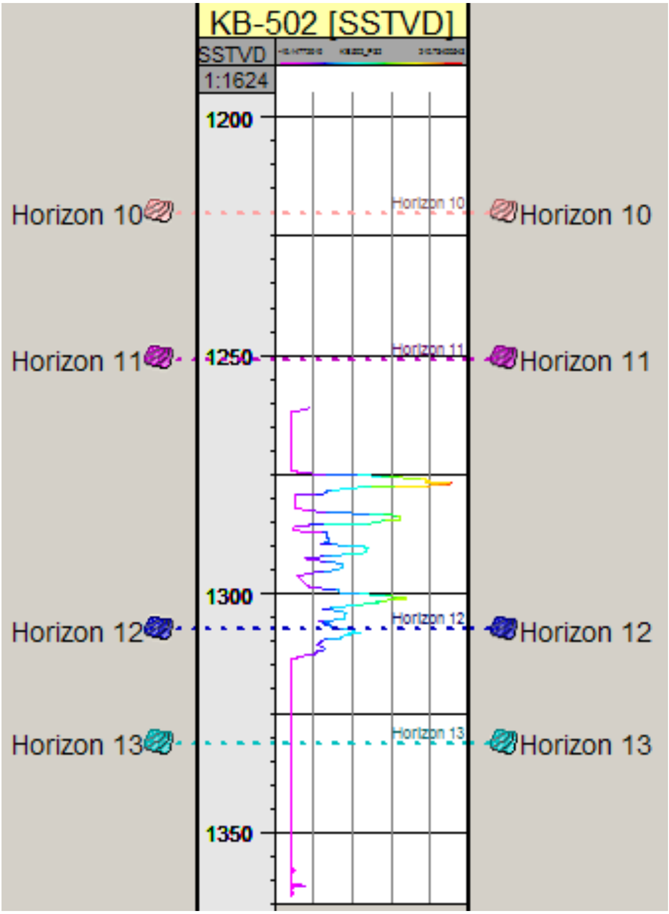
Fracture Intensity P32: Derived from FMI



	Zone ID	P32
Top	# 1	
New Intermediate zone	# 2	
New Intermediate zone	# 3	
Hercynian Unconformity +40	# 4	
Hercynian Unconformity	# 5	
Hercynian Unconformity -40	# 6	
New Intermediate zone	# 7	
End of Fracture	# 8	0.36
Hot Shale	# 9	3.94
New Intermediate zone	# 10	11.70
C20-2 (Cap Rock)	# 11	29.15
C10-3 (Tight Reservoir)	# 12	10.17
C10-2 (Injection zone)	# 13	2.33
Underburden	# 14	
Underburden	# 15	
Underburden	# 16	

Fracture Intensity P32: Derived from FMI





	End of Fracture	Hot Shale	New Intermediate zone	C20-2 (Cap Rock)	C10-3 (Tight Reservoir)	C10-2 (Injection zone)
Zone ID	# 8	# 9	# 10	# 11	# 12	# 13
P32	0.36	3.94	11.7	29.15	10.17	2.33

Fracture Compliance

Layer ID	P32	A = 0.1m		A = 0.25m		A = 0.5m		A = 1.0m	
		Bn m/GPa	Bs m/GPa	Bn m/GPa	Bs m/GPa	Bn m/GPa	Bs m/GPa	Bn m/GPa	Bs m/GPa
# 8	0.36	0.0209	0.0252	0.0523	0.0631	0.1047	0.1261	0.2094	0.2522
# 9	3.94	0.0163	0.0190	0.0407	0.0476	0.0813	0.0951	0.1627	0.1903
# 10	11.70	0.0164	0.0190	0.0409	0.0476	0.0818	0.0952	0.1637	0.1903
# 11	29.15	0.0159	0.0190	0.0399	0.0474	0.0797	0.0949	0.1594	0.1898
# 12	10.17	0.0149	0.0175	0.0373	0.0439	0.0746	0.0877	0.1491	0.1754
# 13	2.33	0.0152	0.0178	0.0379	0.0446	0.0758	0.0892	0.1516	0.1783

Fracture compliance is modeled by assuming open penny-shaped fractures in the "intact" layer with different crack radius a = 0.1, 0.25, 0.5 and 1.0 meters respectively. The crack radius is a proxy for the "open" length of the fracture at grid scale (fracture surface is rough and the opening length is a proxy for its compliance).

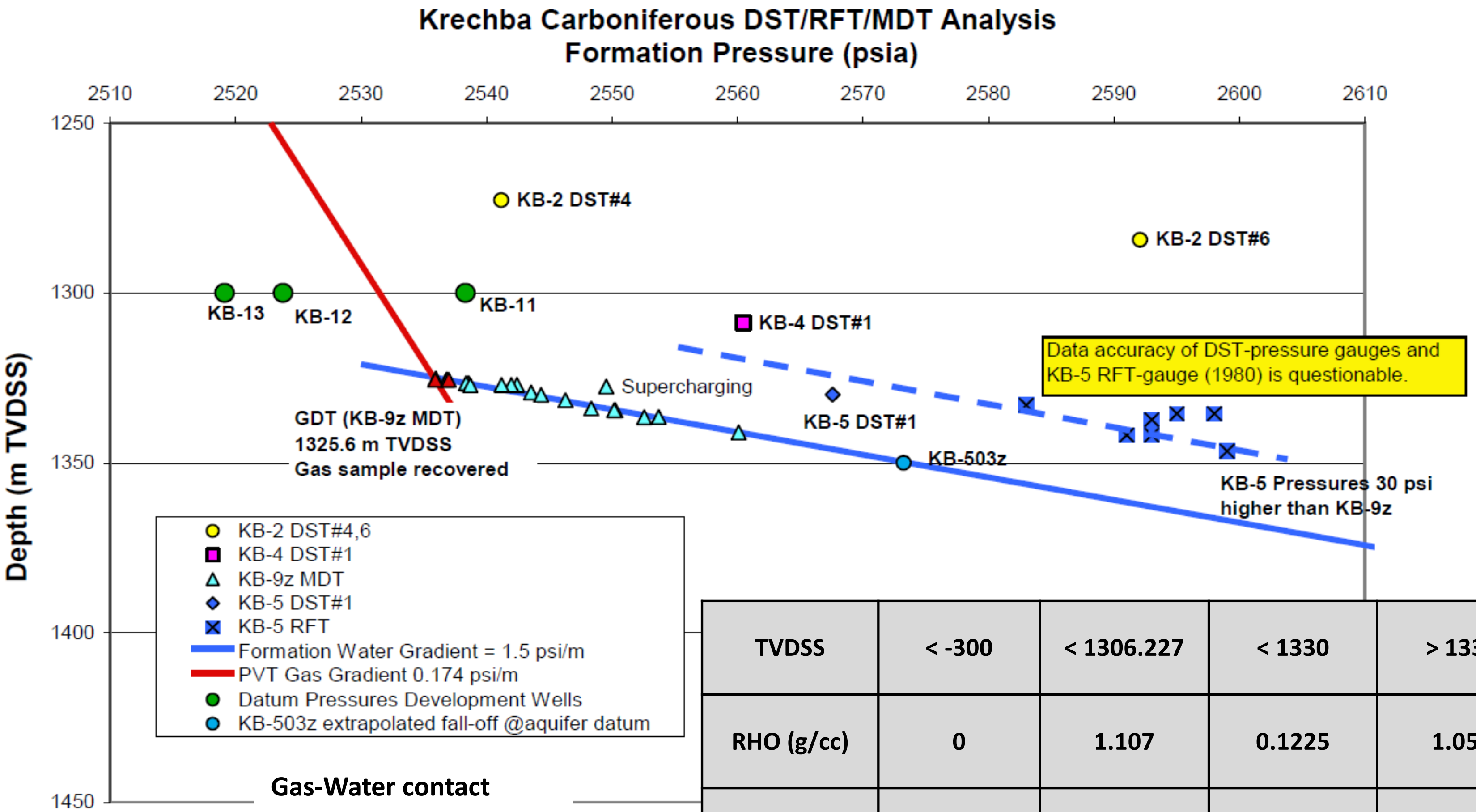
Grid-scale Properties (Including Fractures)

Layer ID	P32	A = 0 (Intact)		A = 0.1m		A = 0.25m		A = 0.5m		A = 1.0m	
		YME	PR	YME	PR	YME	PR	YME	PR	YME	PR
# 1		11.1	0.223	11.1	0.223	11.1	0.223	11.1	0.223	11.1	0.223
# 2		11.9	0.283	11.9	0.283	11.9	0.283	11.9	0.283	11.9	0.283
# 3		20.3	0.345	20.3	0.345	20.3	0.345	20.3	0.345	20.3	0.345
# 4		23.5	0.336	23.5	0.336	23.5	0.336	23.5	0.336	23.5	0.336
# 5		24.0	0.334	24.0	0.334	24.0	0.334	24.0	0.334	24.0	0.334
# 6		20.2	0.344	20.2	0.344	20.2	0.344	20.2	0.344	20.2	0.344
# 7		20.6	0.345	20.6	0.345	20.6	0.345	20.6	0.345	20.6	0.345
# 8	0.36	22.5	0.340	21.3	0.323	19.8	0.303	17.9	0.279	15.3	0.250
# 9	3.94	30.0	0.290	19.8	0.212	15.0	0.194	12.1	0.195	10.1	0.205
# 10	11.70	30.0	0.280	14.2	0.188	10.8	0.196	9.3	0.208	8.4	0.217
# 11	29.15	30.0	0.320	10.9	0.213	9.0	0.227	8.3	0.235	7.9	0.240
# 12	10.17	32.6	0.300	16.1	0.199	12.2	0.203	10.4	0.213	9.3	0.223
# 13	2.33	32.0	0.300	24.0	0.237	18.9	0.208	15.2	0.198	12.3	0.202
# 14		40.0	0.257	40.0	0.257	40.0	0.257	40.0	0.257	40.0	0.257
# 15		40.0	0.257	40.0	0.257	40.0	0.257	40.0	0.257	40.0	0.257
# 16		40.0	0.257	40.0	0.257	40.0	0.257	40.0	0.257	40.0	0.257

A is crack radius (in meter)

Initialized Pore Pressure Distribution

– PPG from BP's Review



Gas-Water contact
- **1330 m (TVDSS)**
- **~2535 psi (175 bar)**

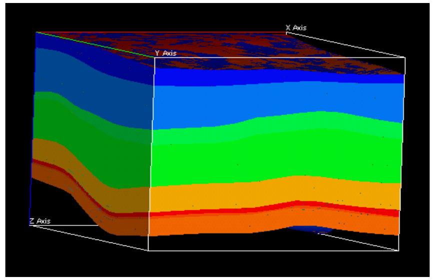
TVDSS	< -300	< 1306.227	< 1330	> 1330
RHO (g/cc)	0	1.107	0.1225	1.056
PPG (psi/m)	0	1.573	0.174	1.501

Initial Stress Reconstruction: Integrate all information

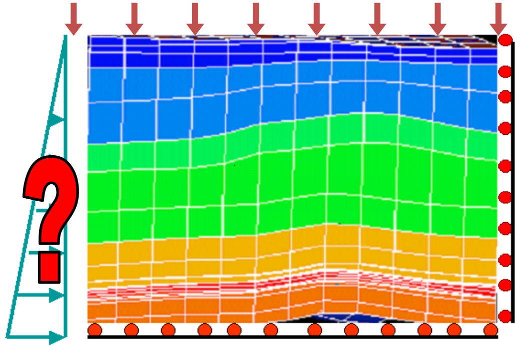
Local Stress data (incomplete)

Minifracs, XLOT, Sonic scanner …

Geological Model

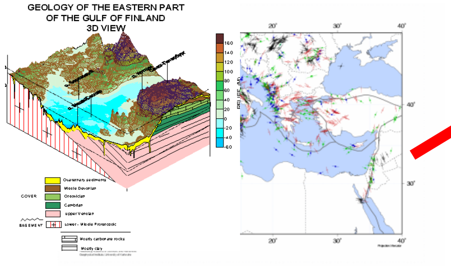


Stress / displacement boundary conditions ?

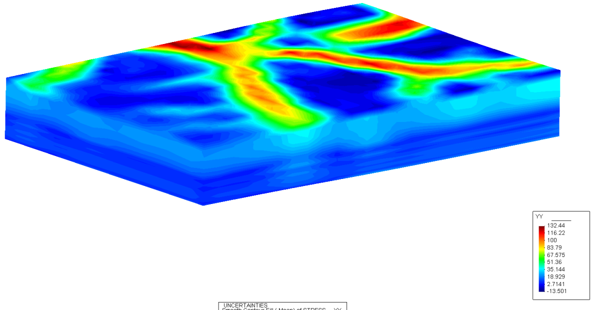


An Inverse Problem…

Geological qualitative knowledge



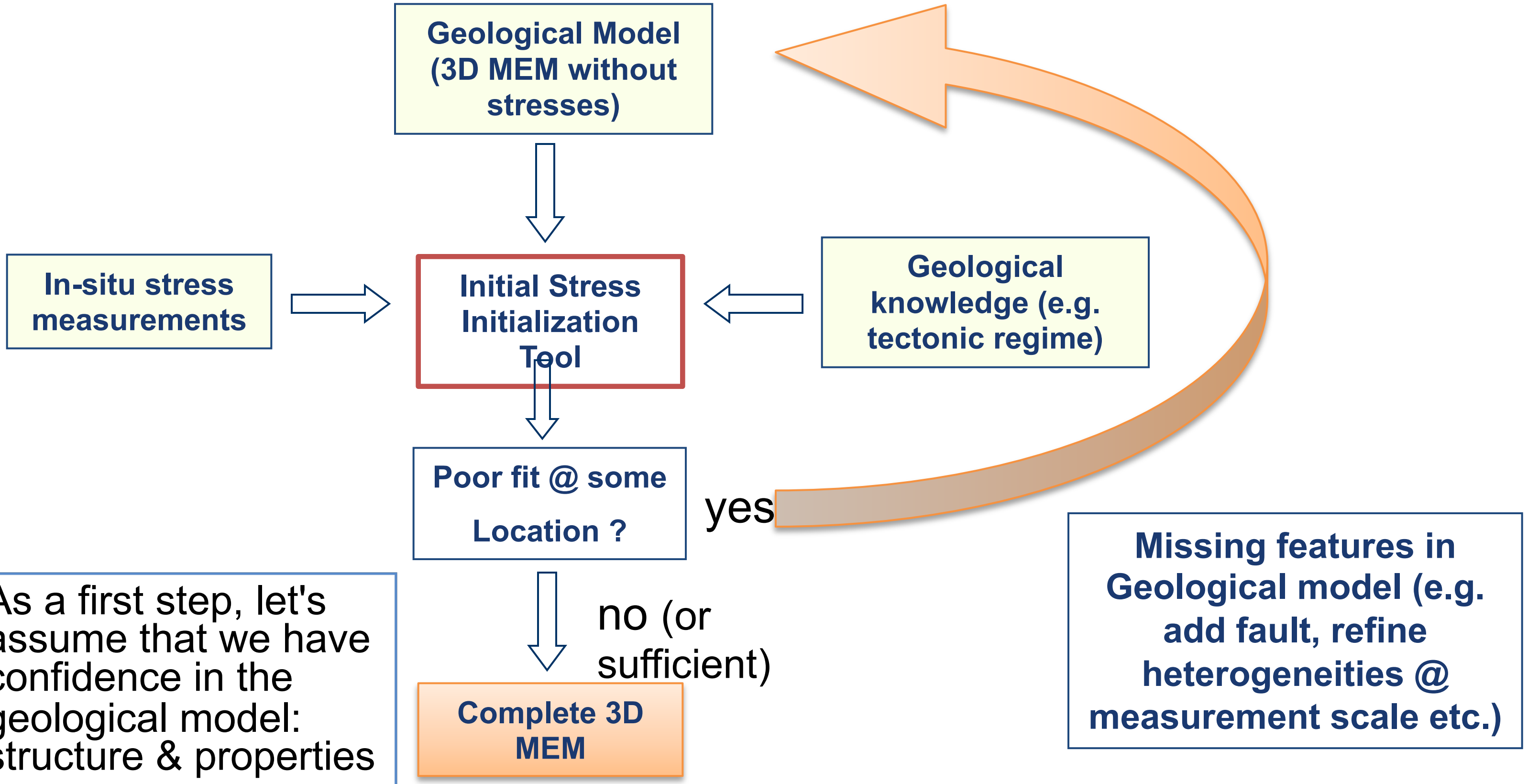
Bayesian Inversion for the far-field tectonic strain (e.g. extension, bending etc.)



Proprietary SLB algorithm

[Intouch Content ID 5315841]

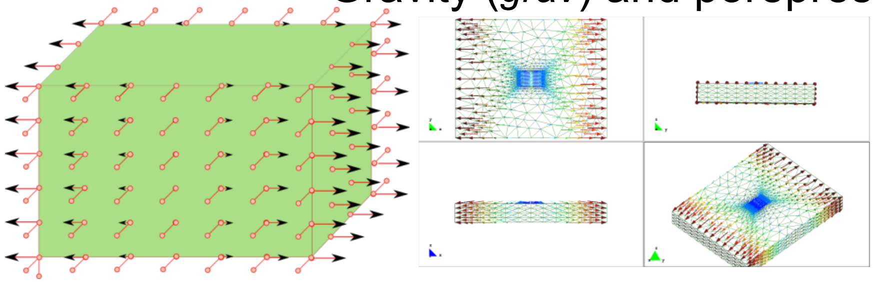
Position in the Geomechanics simulation workflow

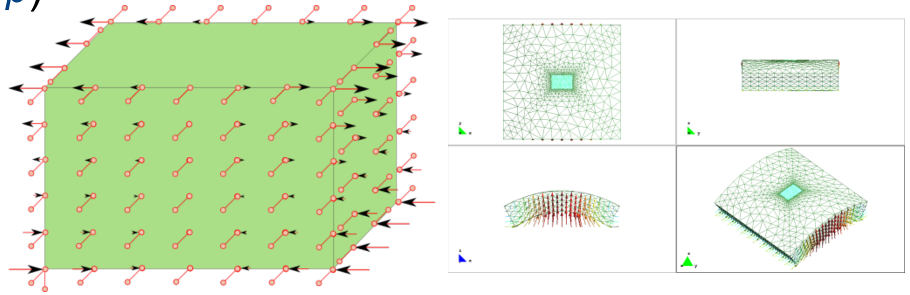


- As a first step, let's assume that we have confidence in the geological model: structure & properties
- Invert for tectonic activity

Boundary conditions as unknowns

- Keep it simple !
  - Horizontal constant strain BC: Shortening / extension modes via a 2D uniform strain tensor: e_x, e_y, e_xy
  - Linear gradient with depth for each of theses variables (bending modes): f_x, f_y, f_xy
  - Gravity (*grav*) and porepressure (*pp*)





$$\mathbf{m} = \left(e_x, e_y, e_{xy}, f_x, f_y, f_{xy}\right)$$

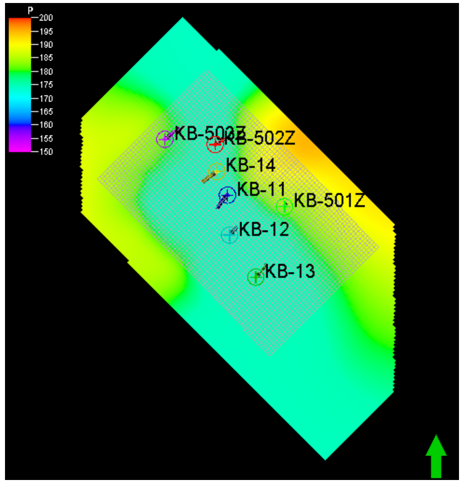
6 unknowns

- Superposition of 8 Fundamental elastic problems:
  - 1 gravity loading + 1 pore pressure loading + 6 tectonic loadings (unit intensity)
  - Theorem of superposition in elasticity gives stress at any point x_j:

$$\boldsymbol{\sigma}\left(x_j, \mathbf{m}\right) = \boldsymbol{\sigma}^{grav}\left(x_j\right) + \sum_{q=1,6} m_q \times \boldsymbol{\sigma}^{tect.q}\left(x_j\right) + \boldsymbol{\sigma}^{Pp}\left(x_j\right) - \alpha\left(x_j\right) Pp\left(x_j\right)\mathbf{I}$$

Needs to solve *only* 8 elastic problems ! Computationally efficient

Evolution of Reservoir Pore Pressure: ECLIPSE



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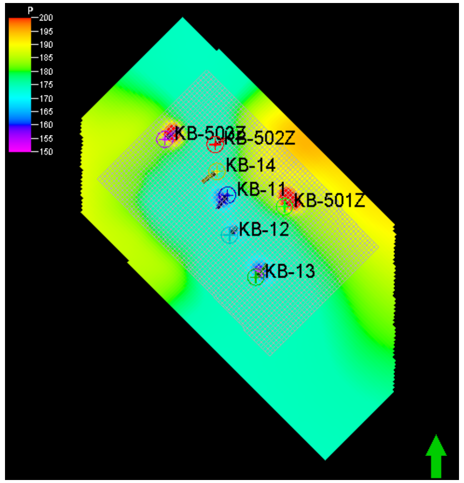
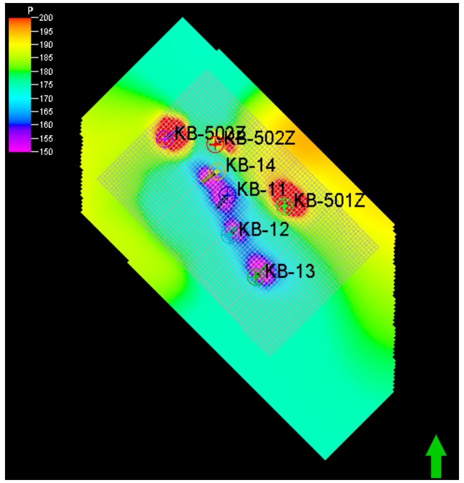


2005-01-22



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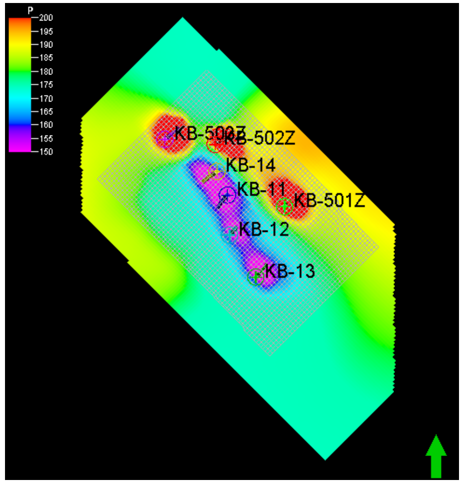

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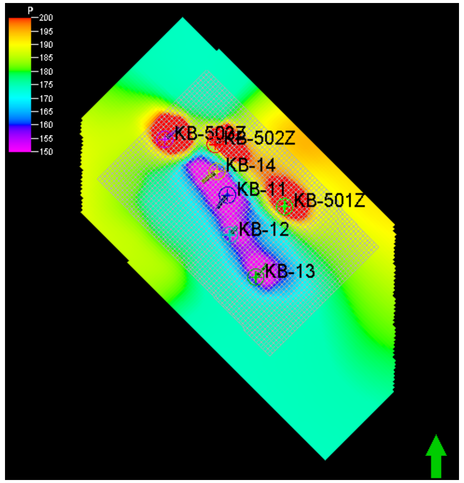

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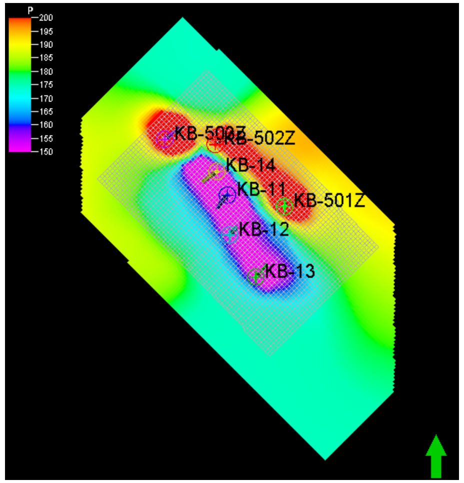
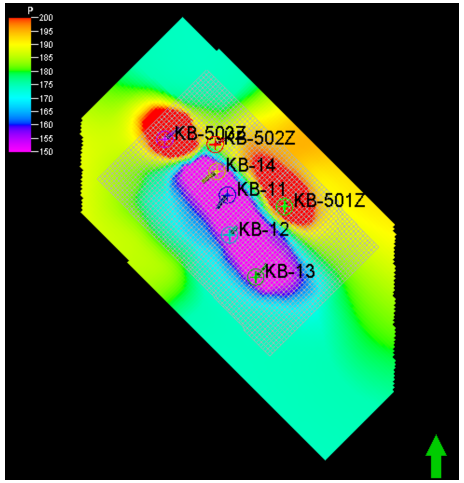
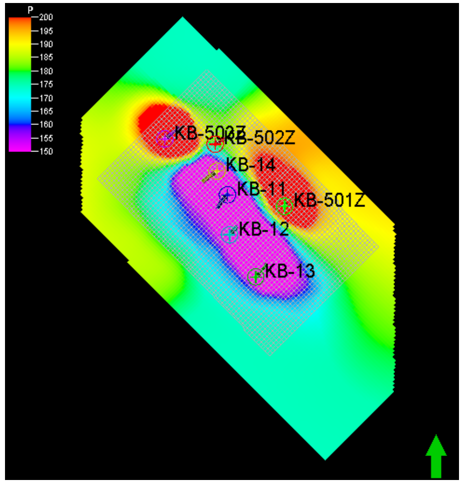


2008-01-01



2009-01-31



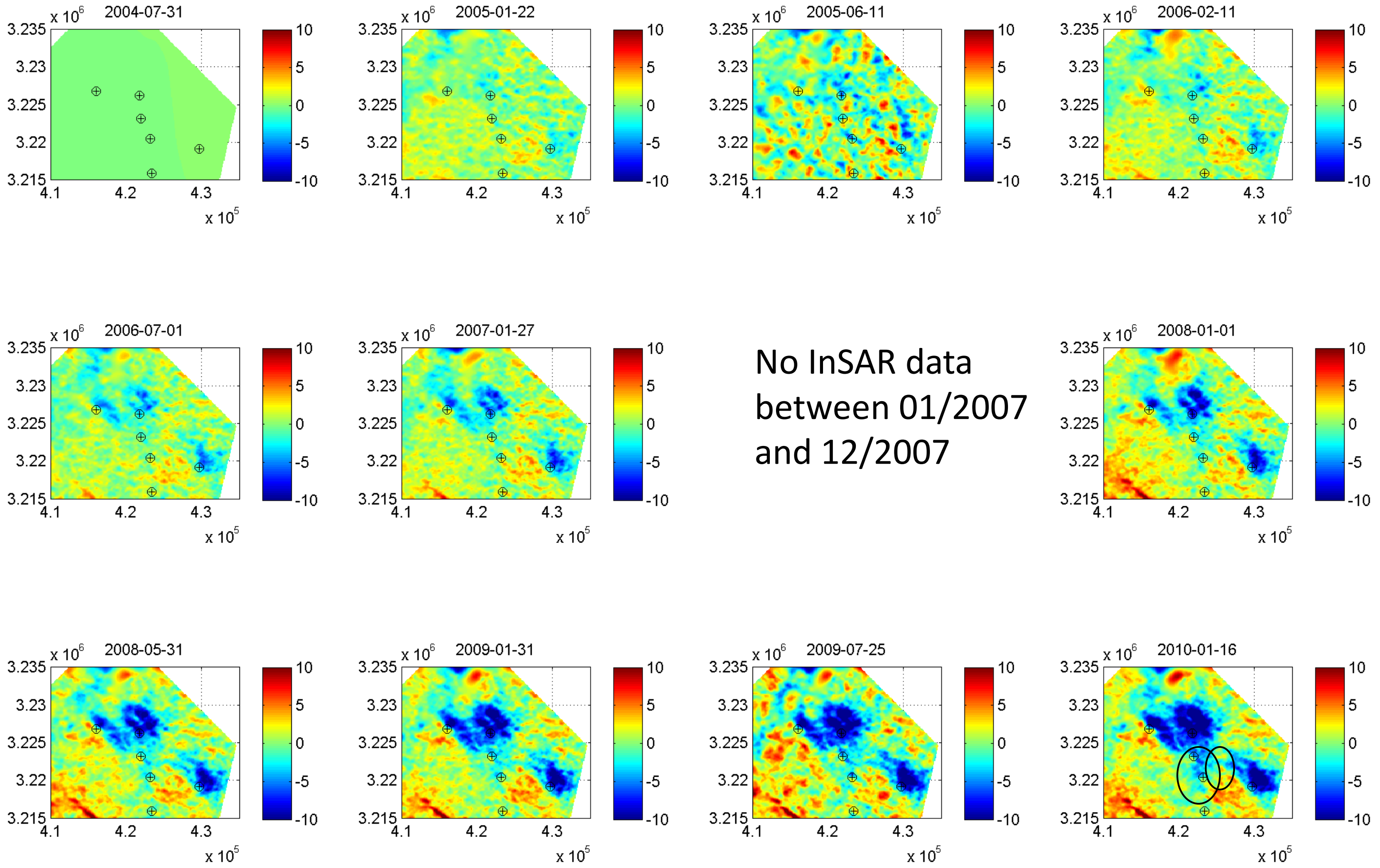
2010-01-16

Difference measurements - predictions (LOS displacement): Model (a=0) vs InSAR

All scales in mm. Difference of the cumulative displacement from the start of the injection between measurements and predictions.

Ground motion (no open fractures):

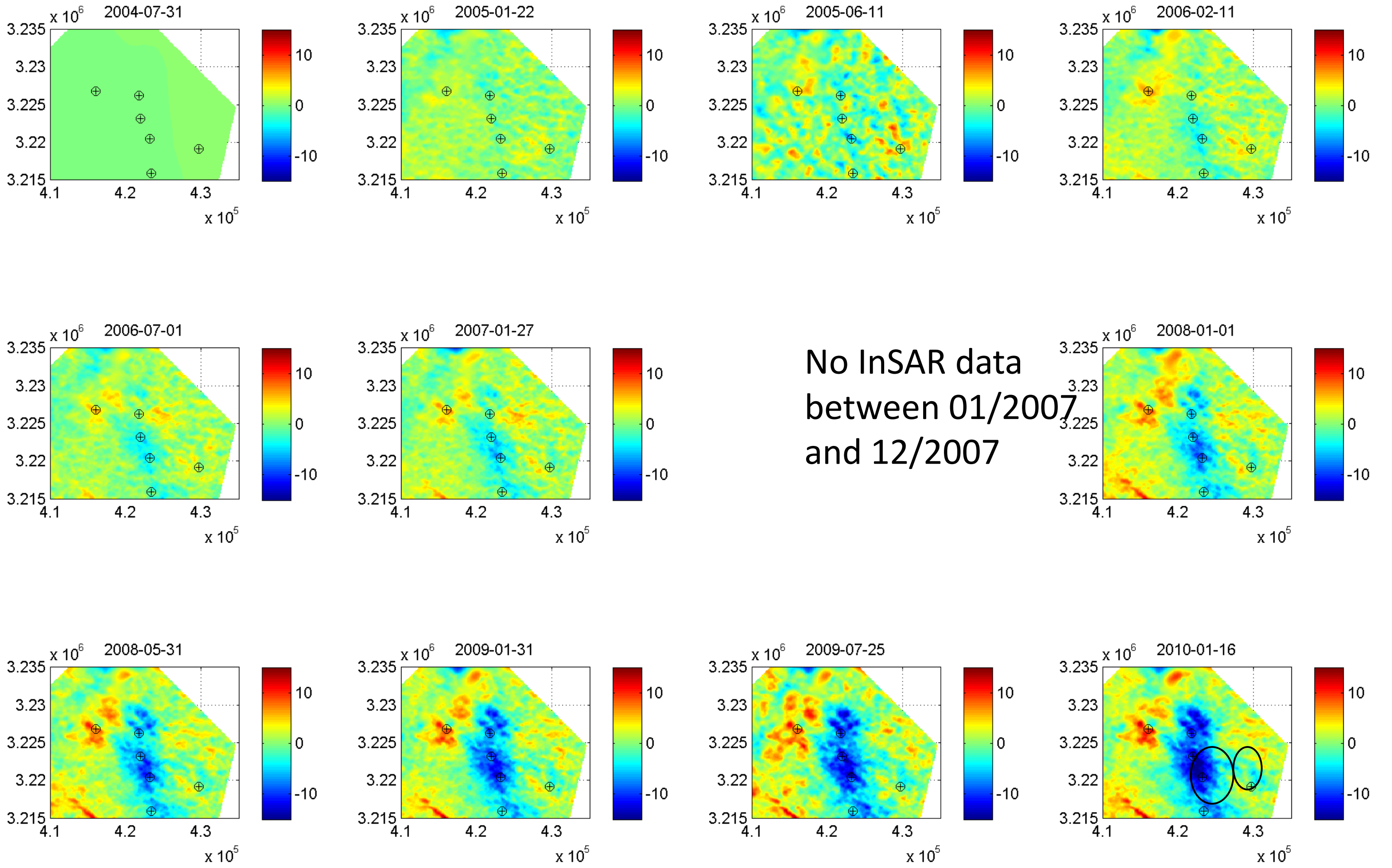
- *correctly* predicted in the production area
- *underestimated* in the injection area



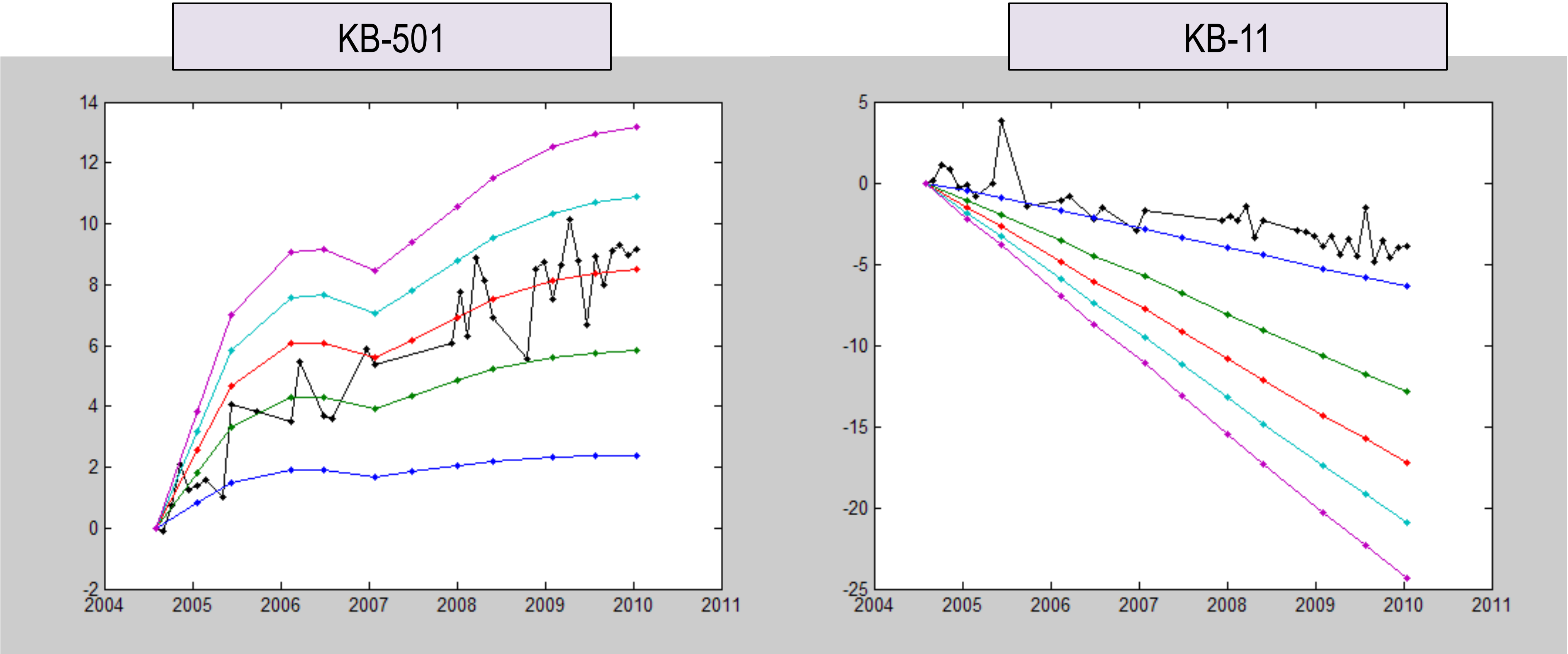
Difference measurements - predictions (LOS displacement): Model (a=0.25) vs InSAR

All scales in mm. Difference of the cumulative displacement from the start of the injection between measurements and predictions.

Ground motion
(no open fractures):
- *correctly* predicted in the production area
- *underestimated* in the injection area



Time evolution of displacement at 2 locations



- The differences between the response of the injection (KB-501) and depletion (KB-11) zones clearly indicates a non-linear dependence of fracture compliance with effective stresses. Fracture compliance remains negligible in the depletion zone (i.e. “closed” fractures) but increase significantly in the injection zone (i.e. “opening” of fractures).