In Salah High-Resolution Heterogeneous Simulations of CO_2 Storage*

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Abstract

The In Salah CO_2 storage site, Algeria, is part of an industrial-scale capture and storage project within the In Salah Gas Joint Venture. CO_2 from several fields within the development is removed from the production stream and injected into a saline aquifer 1900 m below the surface and several kilometers away from one of the gas reservoirs - the Carboniferous sandstone at Krechba.

CO_2, injected into three horizontal wells down-dip from the natural gas field at Krechba, has been actively monitored since the injection start-up in 2004. Satellite surveys (InSAR) showing subtle surface deformation and analysis of well data (gas geochemistry and tracer analysis) give indications of the spatial distribution of the injected CO_2. The 20 meter thick reservoir/aquifer unit is pervasively fractured with the predominant joint set (NW-SE) in close alignment with the present-day stress field. The reservoir/aquifer is also segmented by a number of strike-slip faults (E-W) related to a regional mid-to-late Carboniferous basin inversion. The heterogeneous nature of the storage formation is a key influence on the distribution of stored CO_2 in the subsurface.

We use a non-deterministic stochastic modeling approach assuming capillary limit conditions to simulate the CO_2 migration process. The field-scale model involves 410 million cells with dimensions of 10x10x2 meters. The high-resolution model captures the reservoir heterogeneity with respect to both fault and fracture distributions and uses invasion percolation algorithms to assess the distribution of CO_2 within the storage unit. The simulation results are consistent with the observed CO_2 distribution after 5 years of injection and indicate that the current distribution of CO_2 is principally related to the fracture network. Initial results for predictive simulations of

the post-injection period (decadal distributions) are sensitive to, and principally constrained by, the fault distribution and the multi-phase flow behavior. The simulations results highlight the key role that high-resolution heterogeneous field-scale models can play in developing a comprehensive, cost-effective and fit-for-purpose storage monitoring program. We now aim to model the pressurization of the reservoir near the injection wells to further understand the initial CO_2 distribution and investigate the capillary limit conditions of the invasion percolation model.

Selected References

Boettcher, S.S., S. Mosher, and R.M. Tosdal, 2002, Structural and tectonic evolution of Mesozoic basement-involved fold nappes and thrust faults in the Dome Rock Mountains, Arizona: GSA Special Paper 365, p. 73-97.

Bouasse, H., 1924, Capillarity Phenomena Superficiels: Libairie Delagrave: Paris, Chapter XIII, p. 287-309.

Carruthers, D.J., 2003, Modeling of secondary petroleum migration using invasion percolation techniques, *in* S. Duppenbecker and R. Marzi, editors, Multidimensional Basin Modeling: AAPG/Datapages Discovery Series 7, CD-Rom, p. 21-37.

de Gennes, P-G., F. Brochard-Wyart, and D. Quere, 2003, Capillarity and Wetting Phenomana: Drops, Bubbles, Pearls, Waves: Springer Verlag

England, W.A., A.S. Mackenzie, D.M. Mann, and T.M. Quigley, 1987, The movement and entrapment of petroleum fluids in the subsurface: Journal of the Geological Society (London), v. 144/2, p. 327-347.

Hermanrud, C., H.M.N. Bolas, and G.M.G. Teige, 2005, Seal Failure Related to Basin-scale Processes, *in* P. Boult and J. Kaldi, editors, Evaluating Fault and Cap Rock Seals: AAPG Hedberg Series, 2, p. 13-22.

Iding, M. and P. Ringrose, 2009, Evaluating the impact of fractures on the long-term performance of the In Salah CO2 storage site: Energy Procedia, v. 1/1, p. 2021-2028.

Manzocchi, T., J.J. Walsh, P.A.R. Nell, and G. Yielding, 1999, Fault transmissibility multipliers for simulation models: Petroleum Geoscience, v. 5, p. 53-63.

Manzocchi, T., A.E. Heath, J.J. Walsh, and C. Childs, 2002, The representation of two phase fault-rock properties in flow simulation models: Petroleum Geoscience, v. 8/2.

Meakin, P., G. Wagner, and A. Vedvik, H. Amundsen, J. Feder, and T. Jossang, 2000, Invasion percolation and secondary migration: experiments and simulations: Marine and Petroleum Geology, v. 17/7, p. 777-795.

Poelchau, H.S., D.R. Baker, B. Wygrala, B. Horsfield, and T. Hantschel, 1997, Basin simulation and the design of the conceptual basin model, *in*: D.H. Welte, B. Horsfield, and D.R. Baker, editors. Petroleum and Basin Evolution: Springer, New York, p. 4-70.

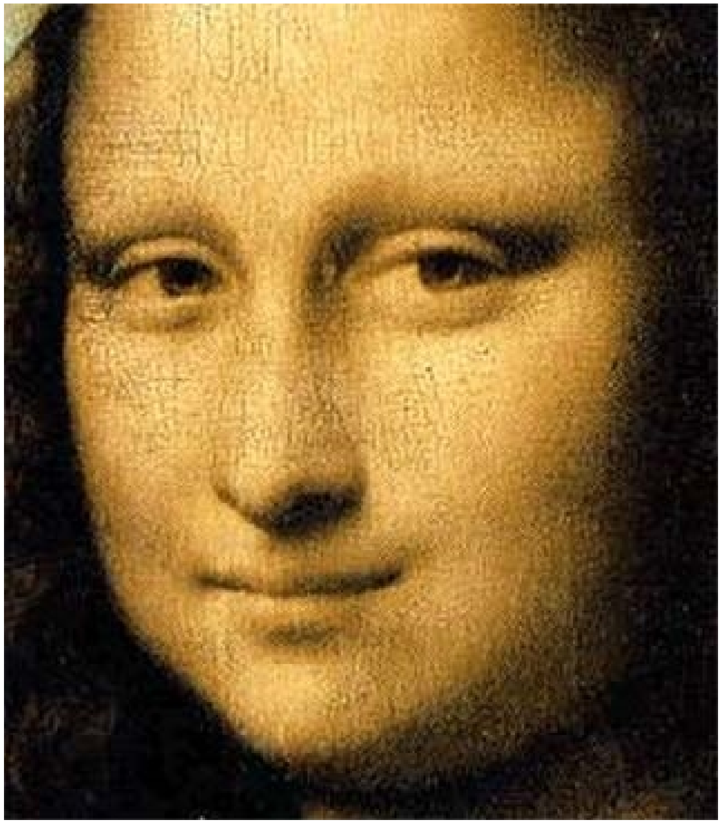
Ringrose, P., M. Atbi, D. Mason, M. Espinassous, O. Myhrer, M. Iding, A. Mathieson, and I. Wright, 2009, Plume development around well KB-502 at the In Salah CO_2 storage site: First Break, v. 27/1, p. 85-89

Ringrose, P. and M. Iding, 2008, Assessing the long-term performance of the In Salah CO_2 storage site: 33rd International Geological Congress, Oslo, Norway, 6-14 August 2008, Abstracts, Web accessed 19 July 2010, http://www.cprm.gov.br/33IGC/1318574.html

Sorkhabi, R. and Y. Tsuji, 2005, Faults, Fluid Flow and Petroleum Traps: AAPG Memoir 85, 342 p.

Website

McGill University Seismic Research Network, Web accessed 19 July 2010, http://csrn.mcgill.ca/main.html

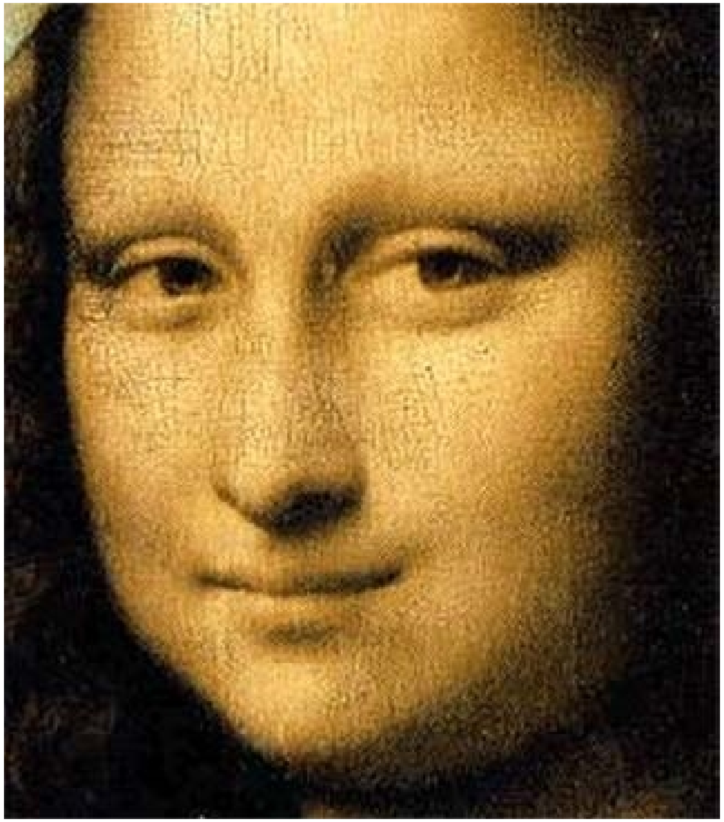


In Salah
High Resolution Heterogeneous Simulations of CO_2 Storage

Andrew Cavanagh
The Permedia Research Group

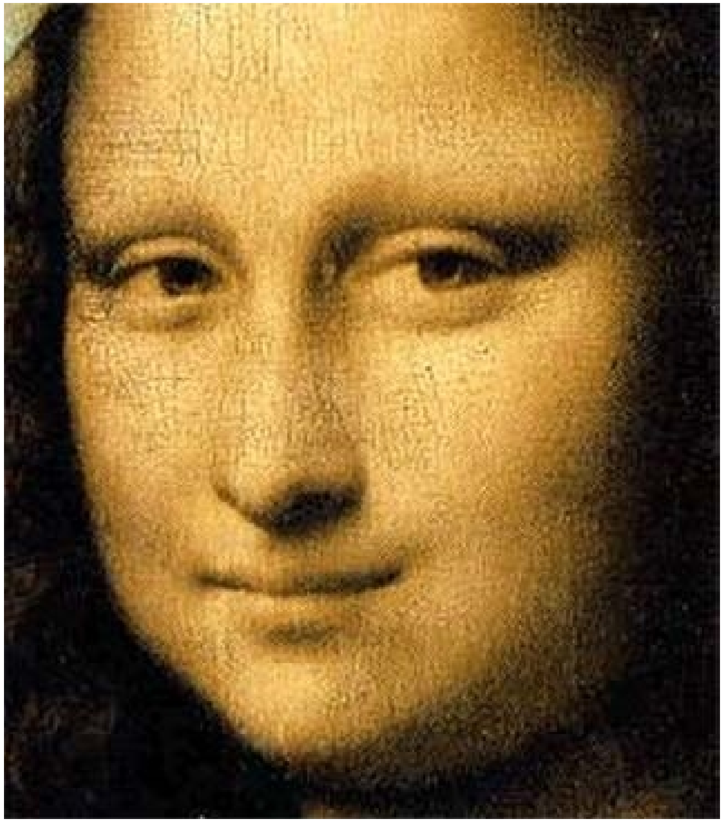
CO2Toolkit by Permedia

In Salah
High Resolution Heterogeneous Simulations…



Mona Lisa: 120,000 pixels

In Salah
High Resolution Heterogeneous Simulations…



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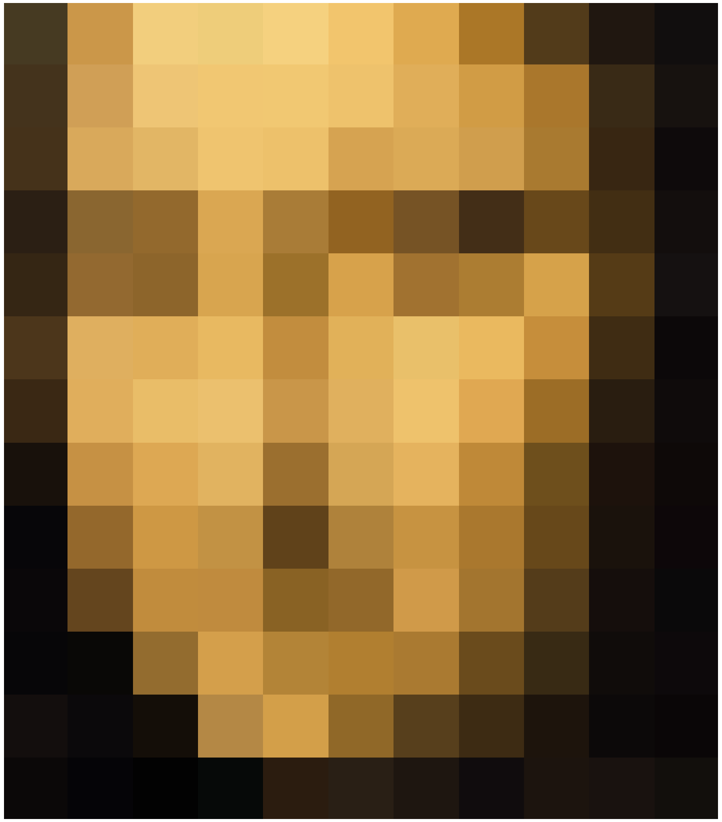

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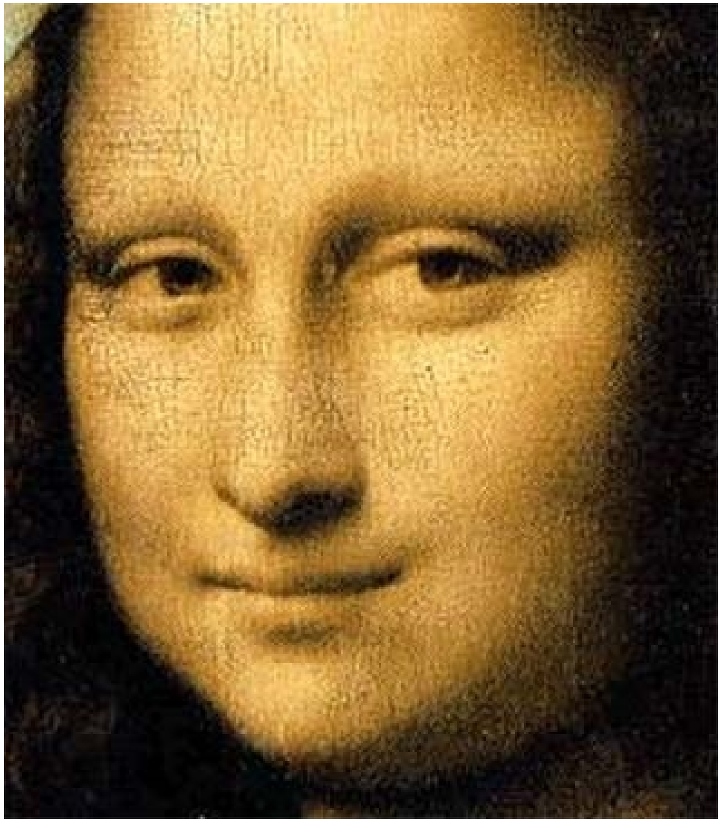
In Salah
High Resolution Heterogeneous Simulations…

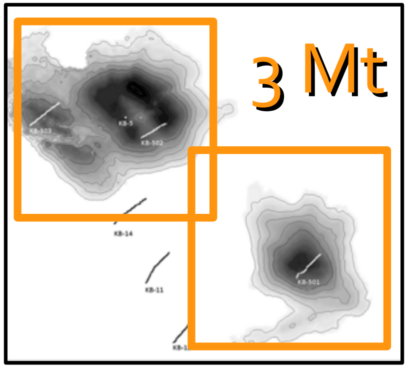


Mona Lisa, Leonardo da Vinci, c. 1519

- Megatonne CO_2 Storage Sites
- In Salah Overview
- Modeling Strategy
  - Flow domains
  - Capillary numbers
- Field Scale Model
- Simulations
  - Pilot
  - Faulted
  - Faulted and Fractured
- Comparison with Observations

Megatonne Storage Sites

In Salah: 20x18 km



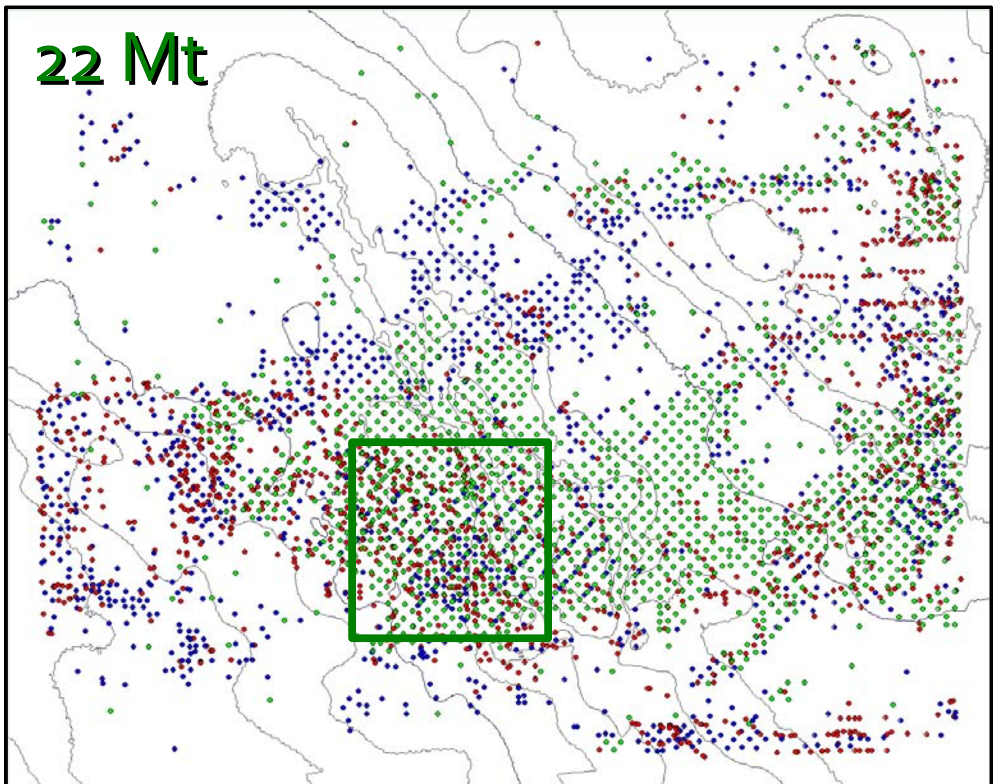
Injection depth

Sleipner: 1000 m

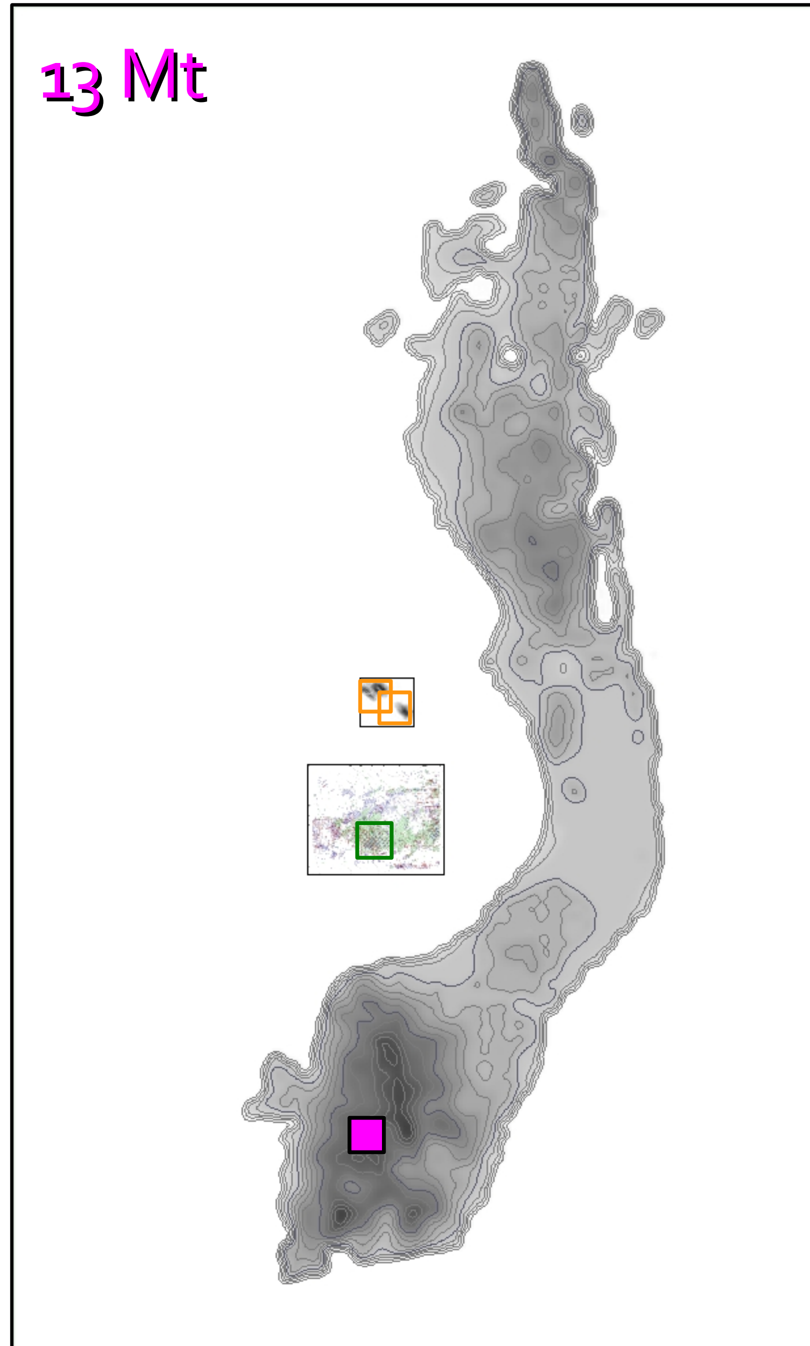
Weyburn: 1400 m

In Salah: 1900 m

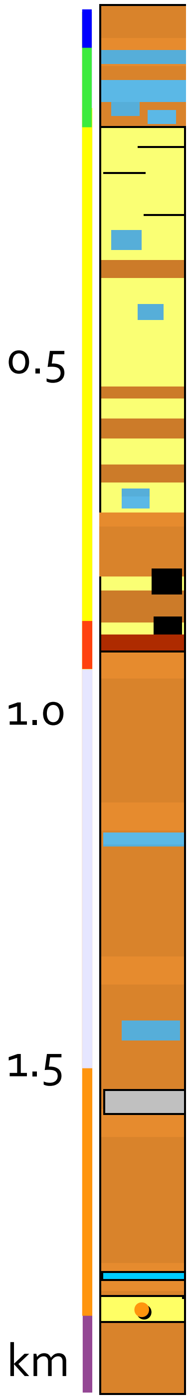
Weyburn-Midale: 50x40 km



Sleipner: 300x400 km



In Salah Stratigraphy



	Tops
• Water table, 450-300 m (msl)	
• Cretaceous Superieur… siltstones and limestones	0 m
• Pan Saharan Aquifer… sandstones with mudstones	170 m
• Regional Hercynian U/C, top of Visean, overlain by thin anhydrite	940 m
• C20-7… fractured mudstones with strong gamma ray response (Visean, Carb)	1590 m
• C20-3… fractured mudstones (Visean, Carb)	1790 m
• C20-2… fractured mudstone with open fracture sets, unstable (Visean, Carb)	1820 m
• C20-1… fractured mudstone thin dolomites and siltstones (Visean, Carb)	1860 m
• C10-3… fractured siltstones and sandstones (Tournasian, Carb)	1885 m
• C10-2… fractured sandstone (Tournasian, Carb)	1900 m
• D70… dolomitic sandstone with thin silt and mudstones (Fammenian, Dev)	1920 m

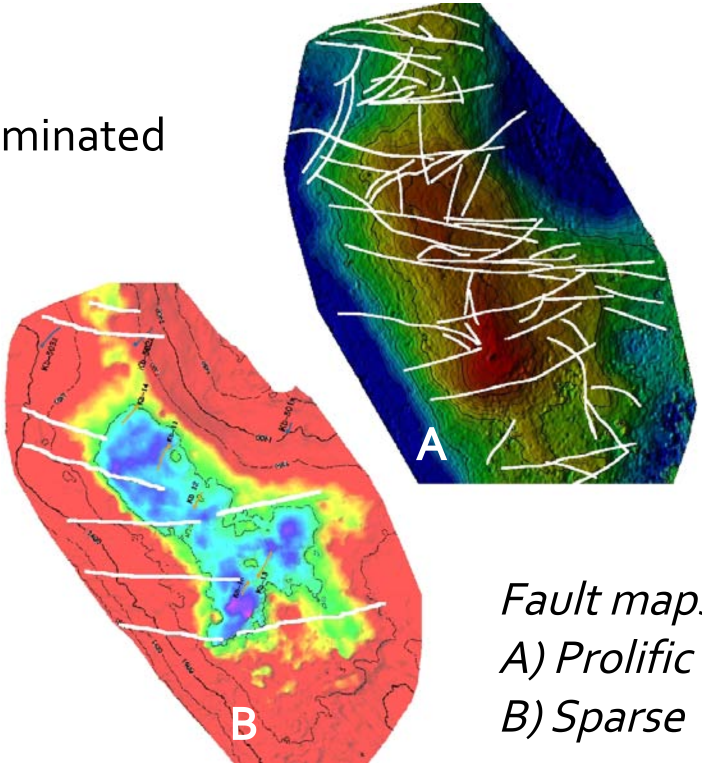
Ages

U Cretaceous	100 - 65 Ma
Sakamarian	288 - 283 Ma
Visean	342 - 327 Ma
Tournasian	354 - 342 Ma
Fammenian	364 - 354 Ma

Visean

In Salah Reservoir

Sandstone: massive, rippled, fracture-influenced, matrix-dominated
Facies: tidal deltaic, deposited in a broad palaeovalley
Porosity: ~15% (13- 20)
Permeability: ~10 md (0.1 - 300)



Fault maps
A) Prolific
B) Sparse

Faults

Fault throw less than 20 meters
No faults cut the reservoir communication
E-W faults easiest to map, N-S faults, NE-SW faults
Prolific and sparse fault models

Fractures

2-sigma plane orientation NW-SE, density: 2-3/meter, aperture: 0.1-1 mm, length: 6-25 m
Fractures conform to recent stress field

Wells, KB-501, -502, -503

Injection rate: 0.2 Mt/yr/well… 30 Mmscf/day… 8 litres/well/second
Horizontal: 1.3 - 1.5 km
Azimuth: perpendicular to stress field
Observations: logged, cored and monitored

Storage Site Observations

3D seismic baseline, downhole geophysics, 4D seismic monitoring,
InSAR: Interferometry Satellite Airborne Radar, geochemical tracers…

Flow Domains and Dimensionless Numbers

Flow Domain	*Flux rate; occurrence*	*Dimensionless number*
Turbulent flow	Very high; near-well, unusual	Re > 10
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Darcy flow	High-to-moderate; near-well	Re < 10, Ca > 0.0001
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Invasion percolation	Low; reservoir and basin-scale	Ca < 0.0001, Kn < 1
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Knudsen flow	Extremely low; unconventional	Kn > 1

Key: Re, Reynolds No.; Ca, Capillary No.; Kn, Knudsen No.

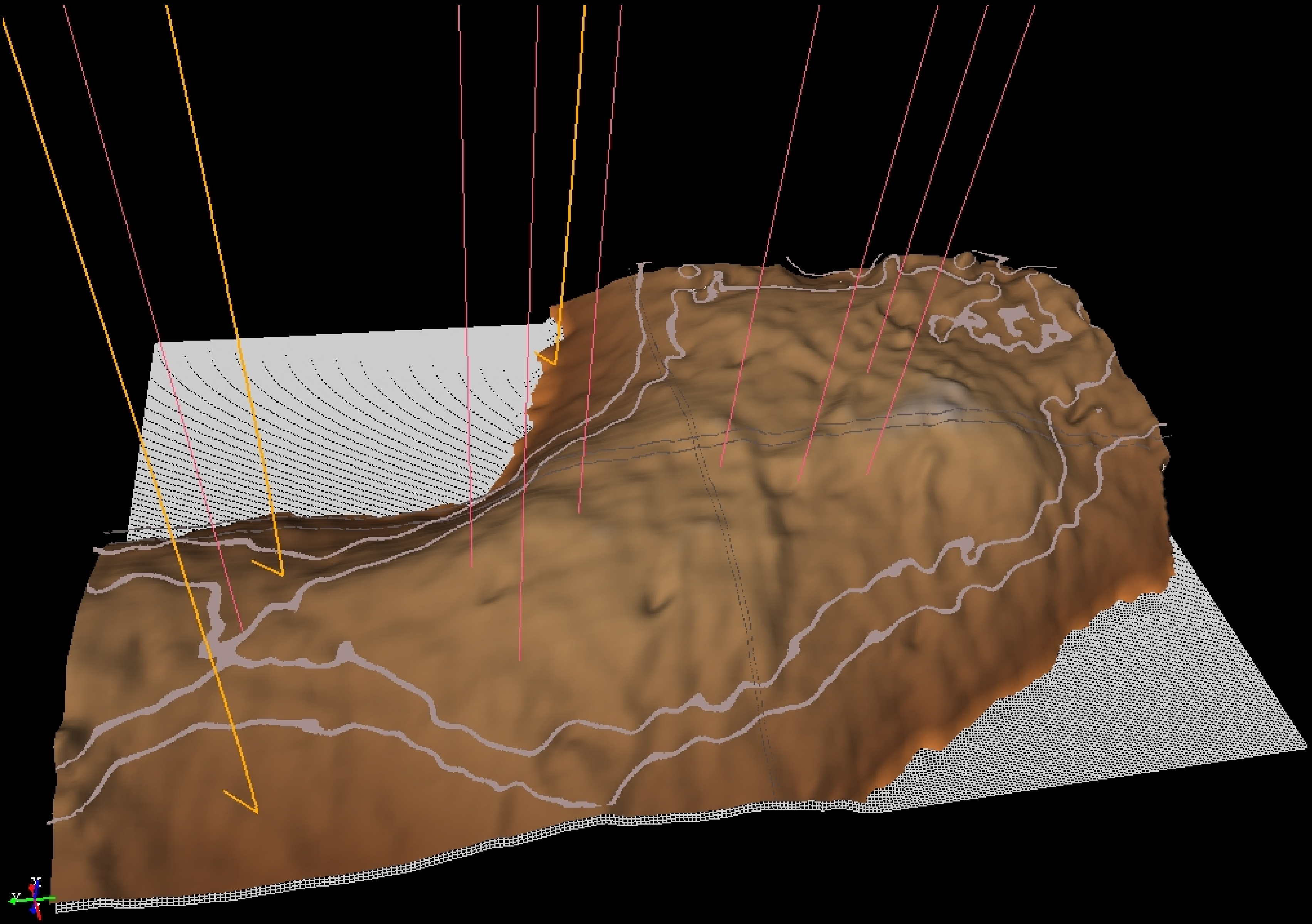
Capillary Number Calculations

Ca = μq/γ	[/]
μ, viscosity	[Pa.s]
q, flux	[m/s]
γ, interfacial tension	[N/m]
Capillary flow ~ E-04	[1:10,000]

(Henri Bouassé, *Capillarity and Wetting Phenomena,* 1924)
(Pierre-Gilles de Gennes, Brochard-Wyart & Quere, *ibid.,* 2003)

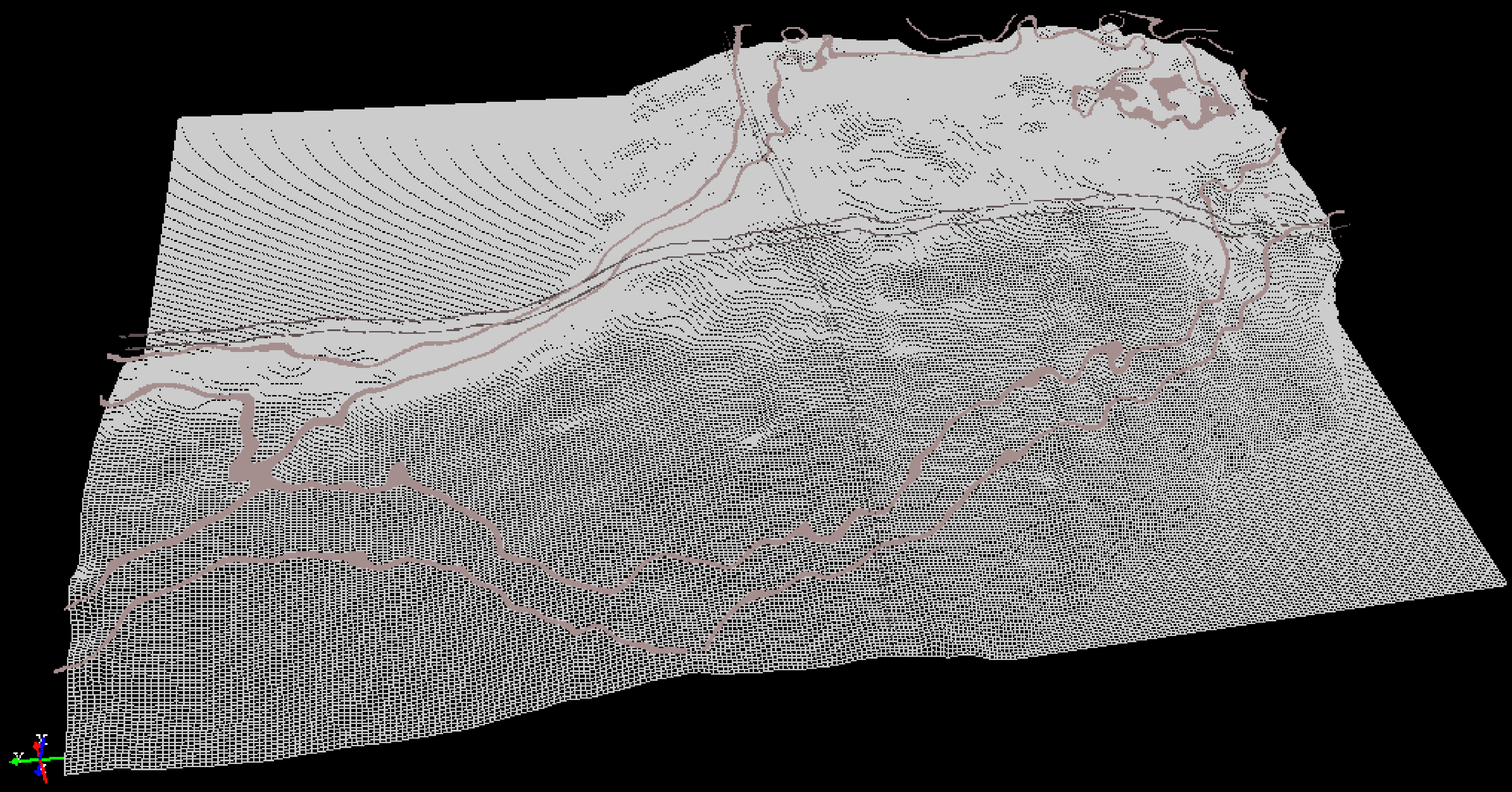
- In Salah injection, Ca ~ E-06 (8 litres/well/second)
- In Salah migration, Ca ~ E-07 (1.3 km/2 years)

Field Scale Model, Invasion Percolation



104 million cells, 17.5x25 km, 20x20x2 m

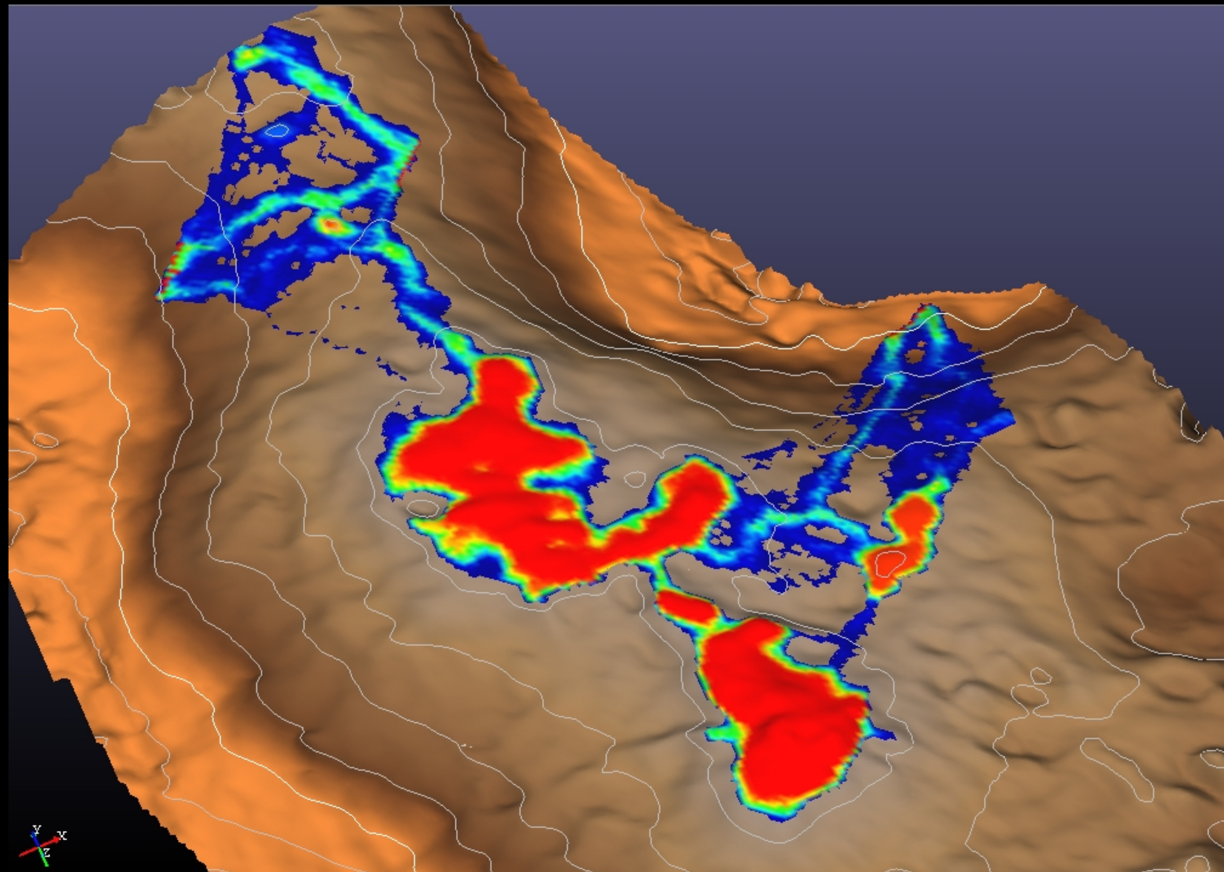
Field Scale Model, Invasion Percolation



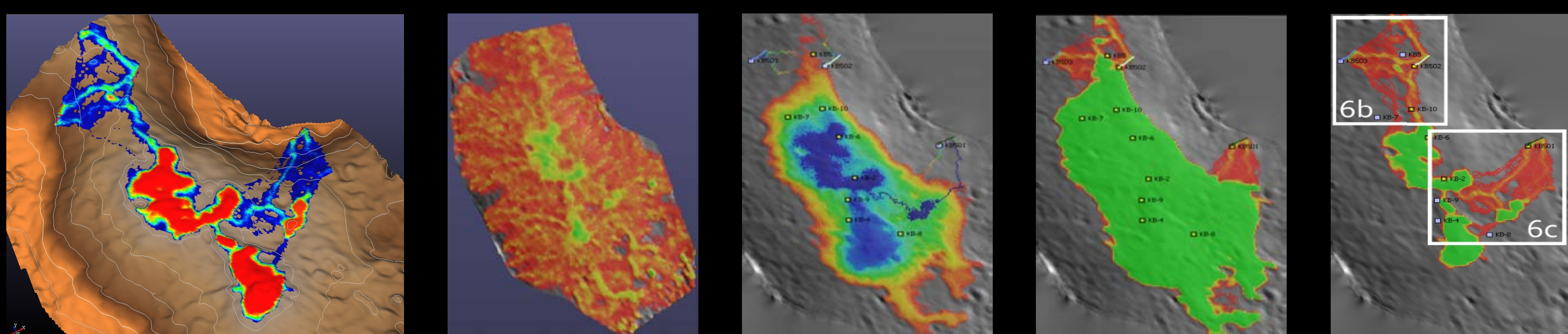
104 million cells, 17.5x25 km, 20x20x2 m

Simulations…

Migration beneath the Caprock

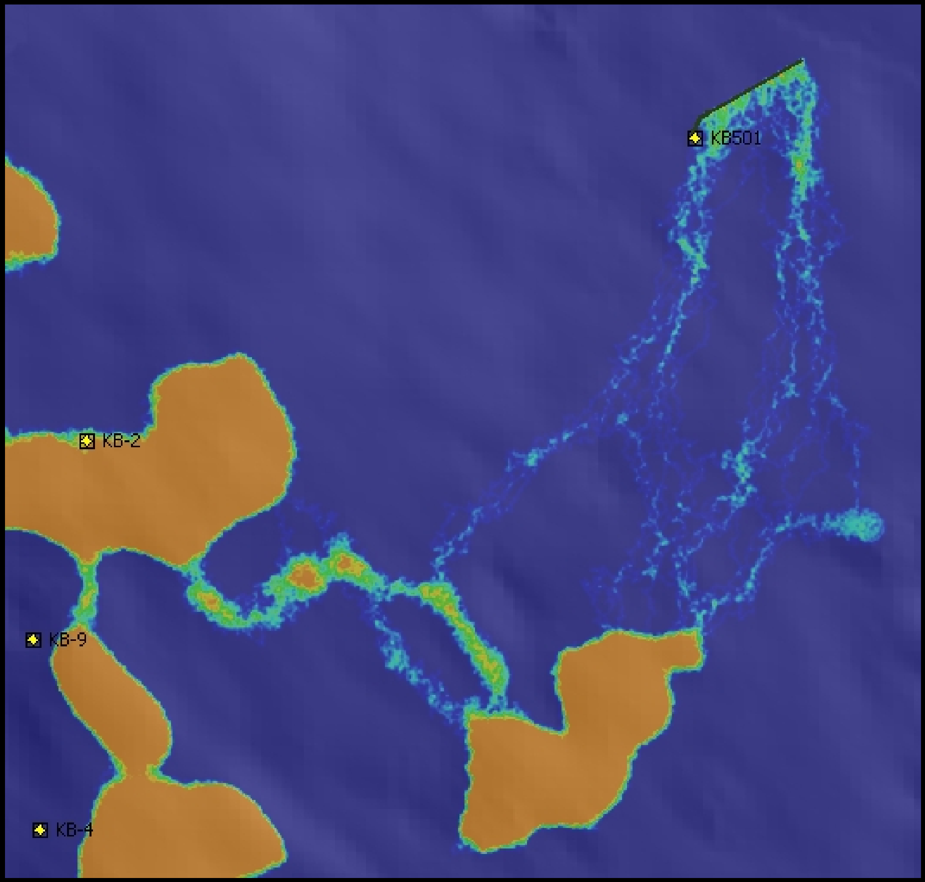


Stochastic analysis of probable migration paths (N=120)

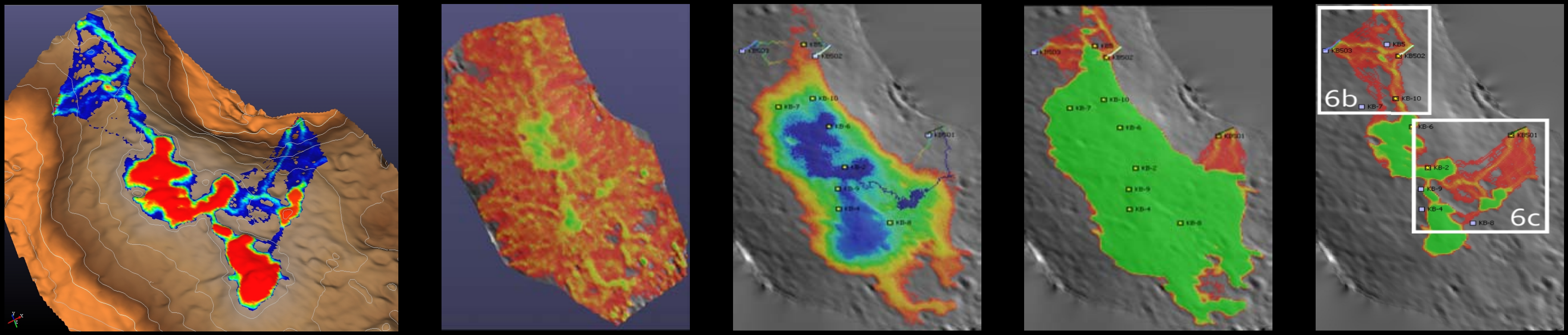


Simulations…

Southern Area

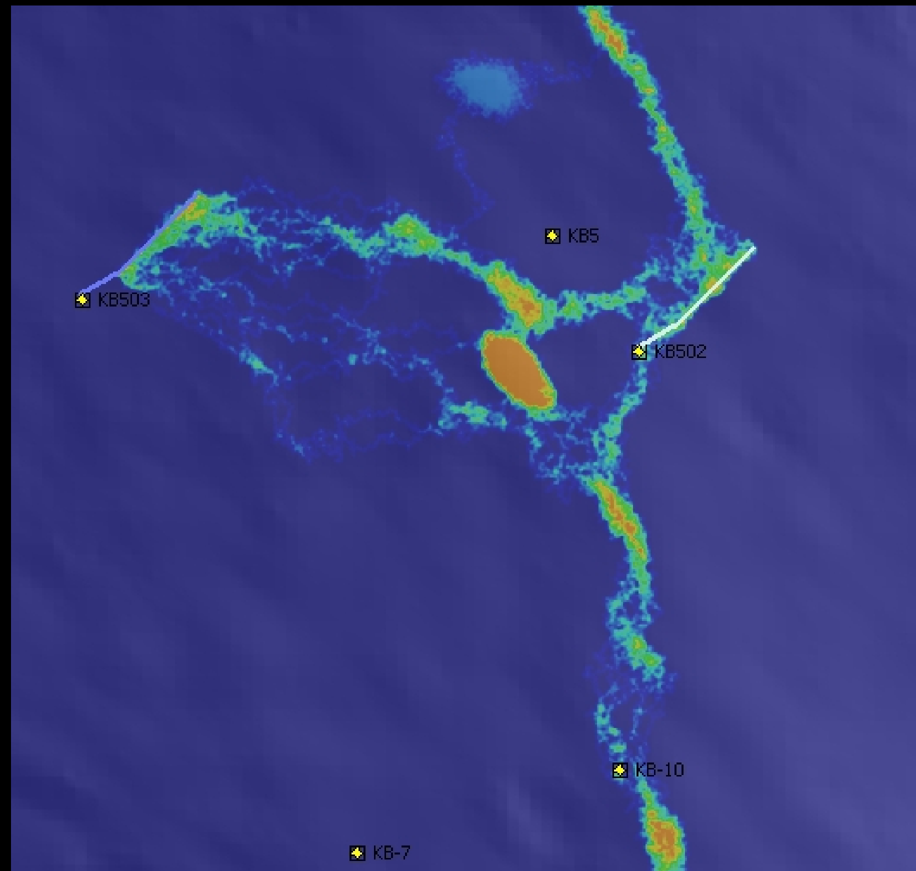


Stochastic analysis for KB-501 (N=55)

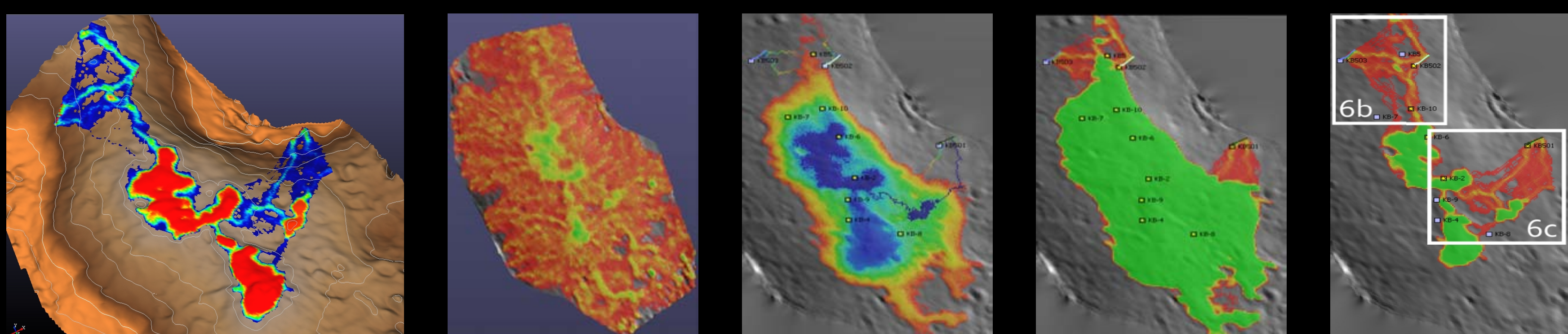


Simulations…

Northern Area

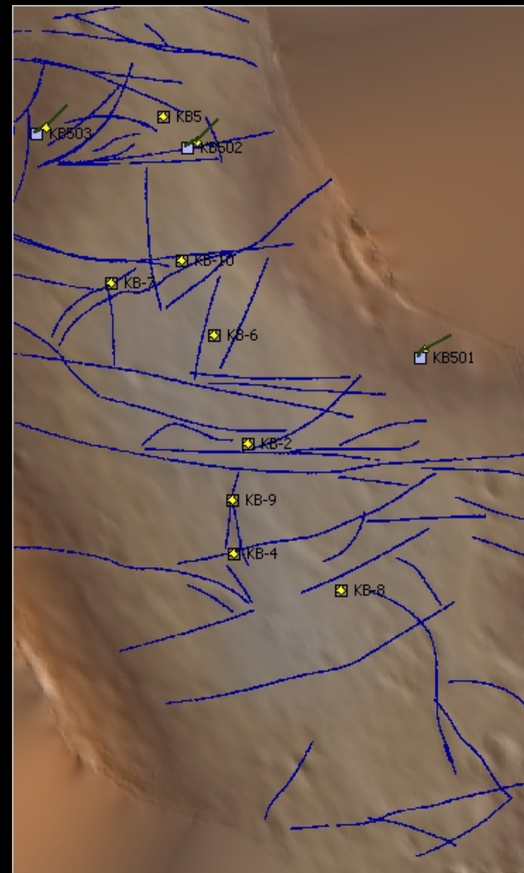


Stochastic analysis for KB-502 & KB-503 (N=55)

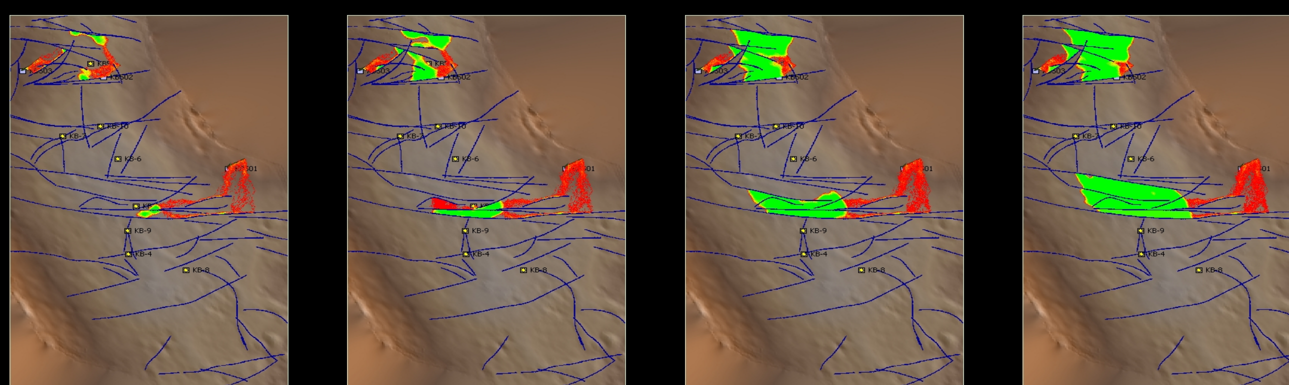


Simulations…

Migration with Faults

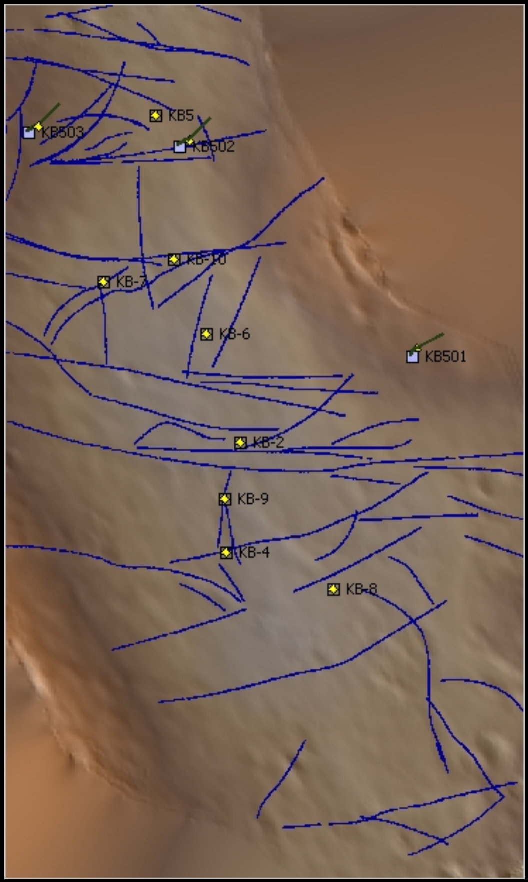


Prolific fault scenario (BP seismic mapping team)

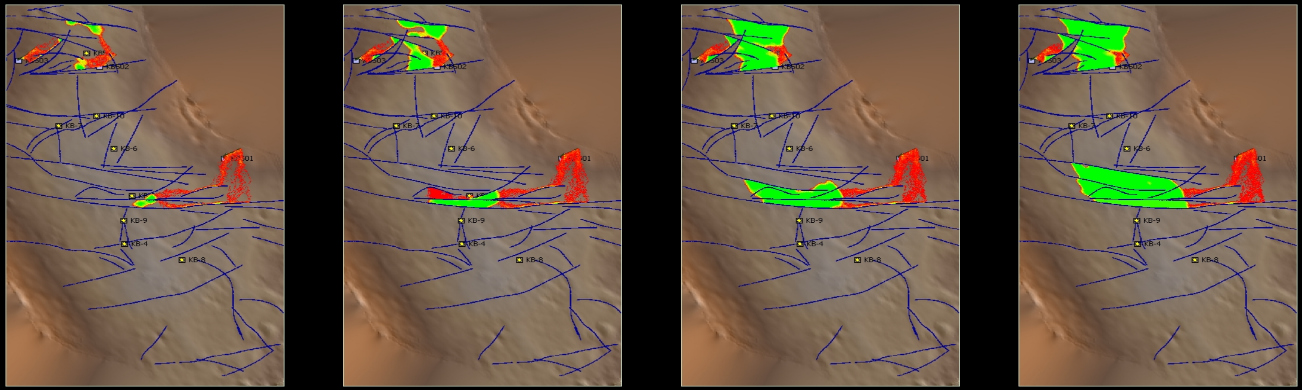


Simulations…

Migration with Faults



5-10-15-20 meter column height (frequency analysis, N=60)



Simulations…

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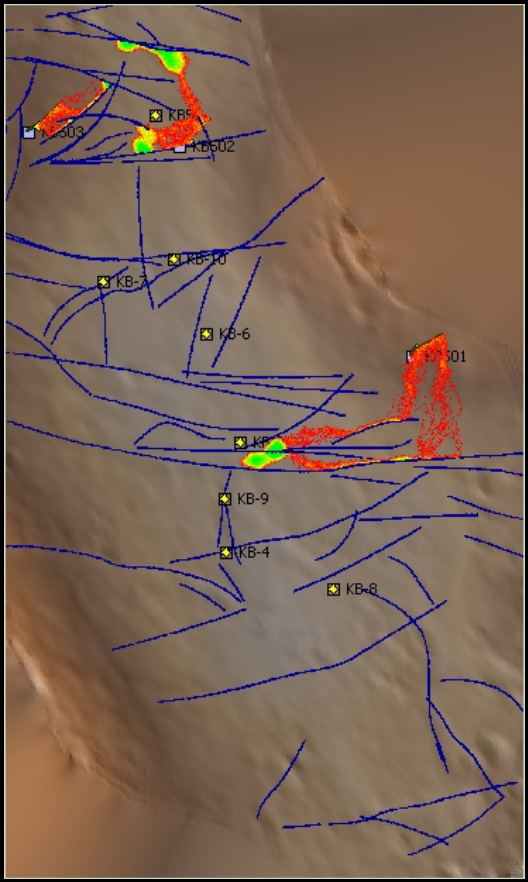

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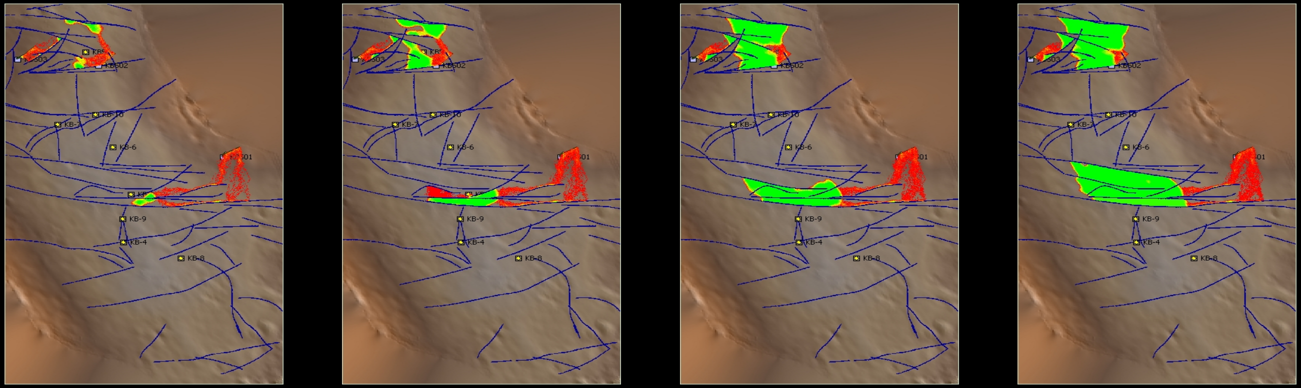

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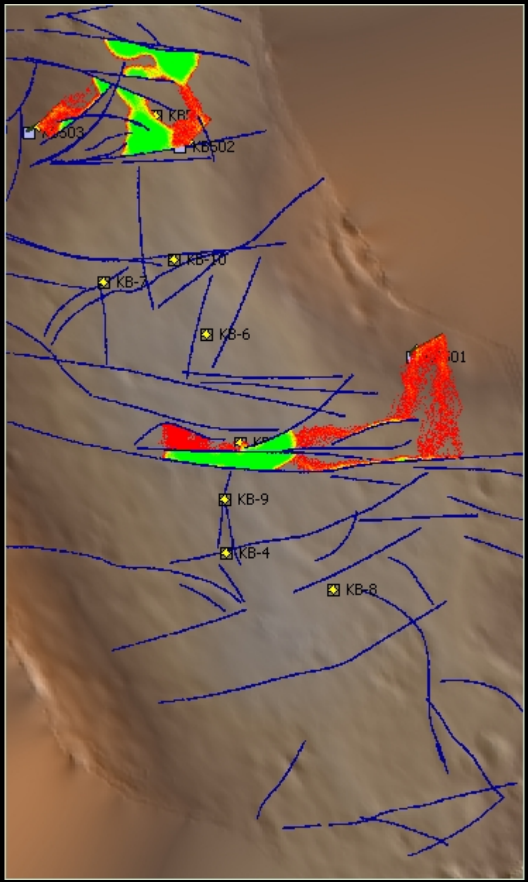

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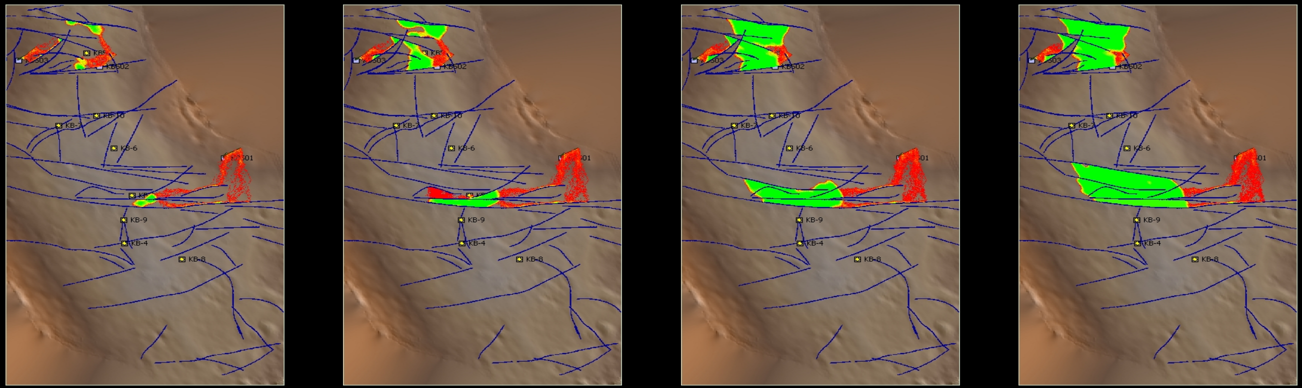

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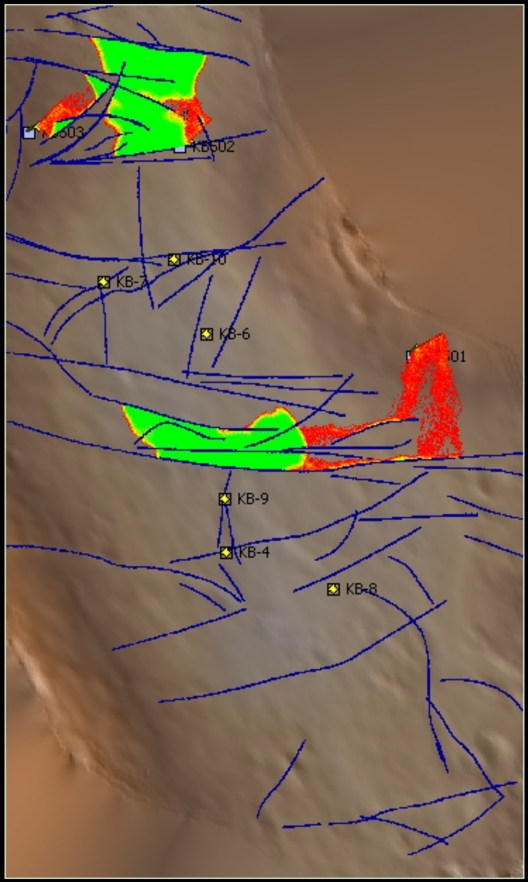

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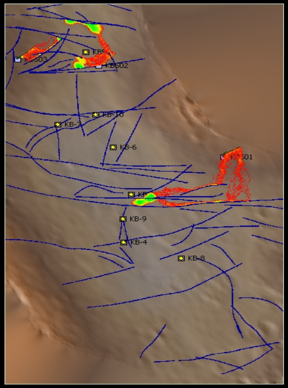

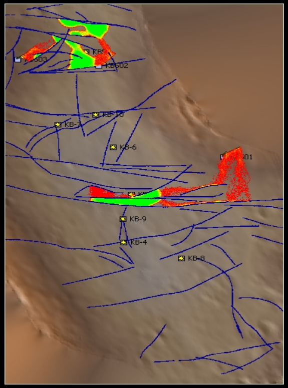

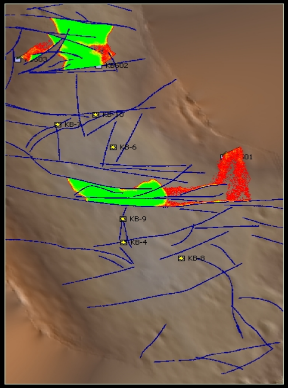

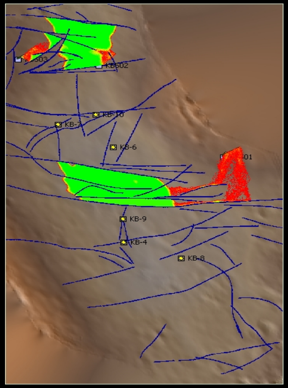

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Migration with Faults

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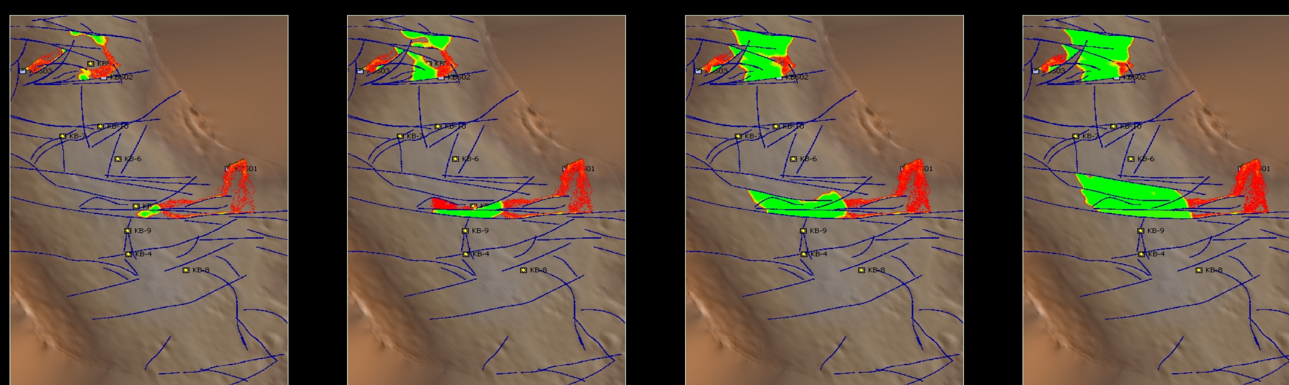
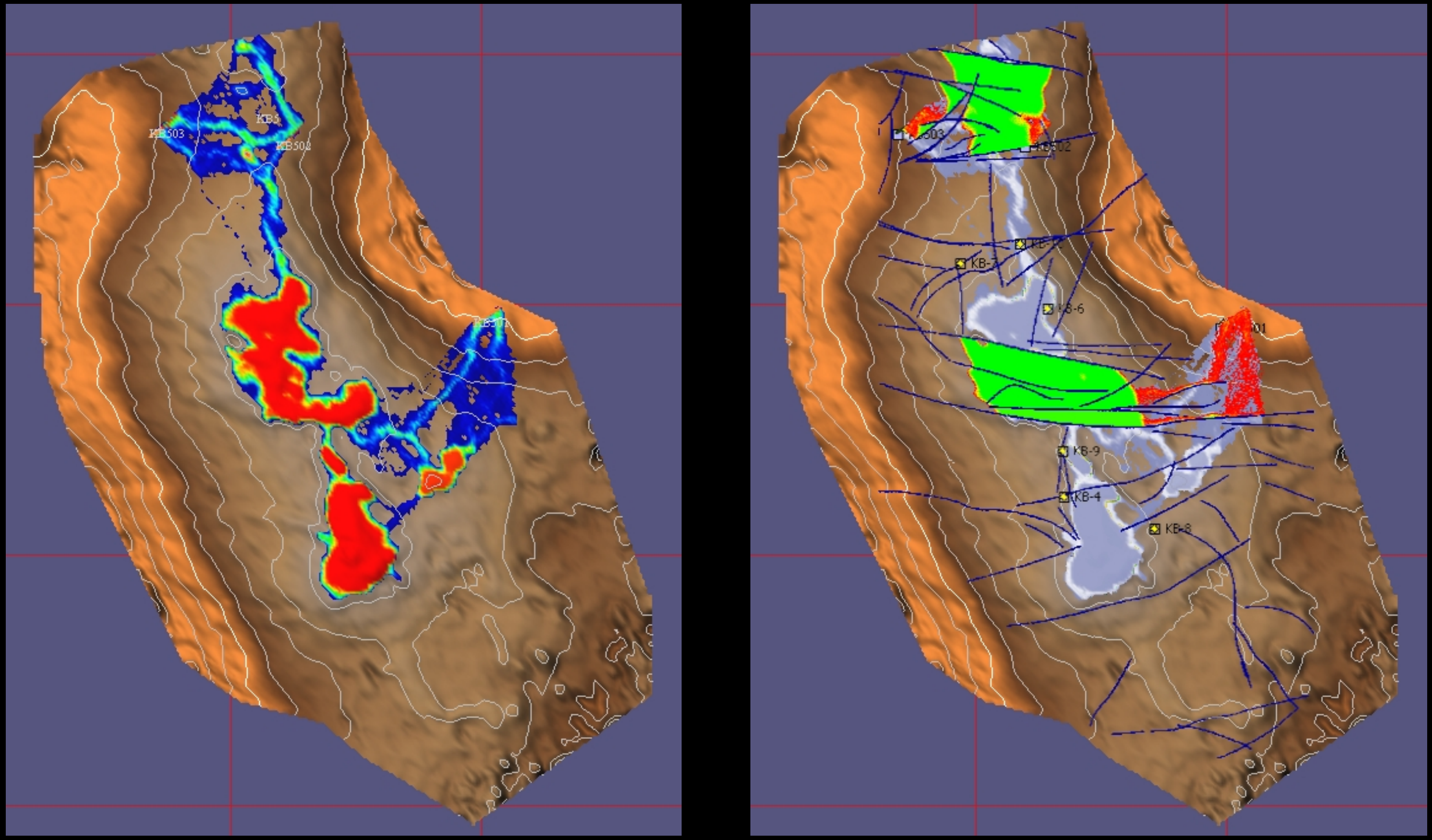
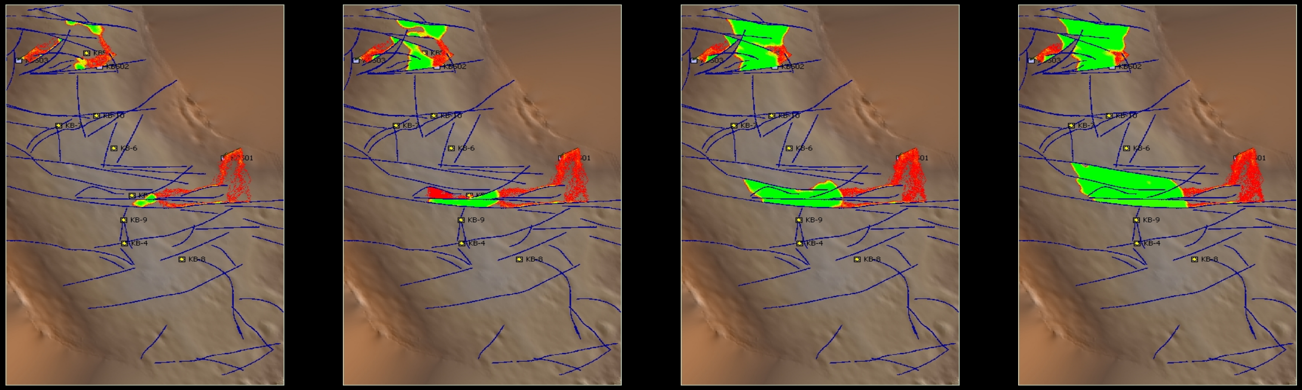


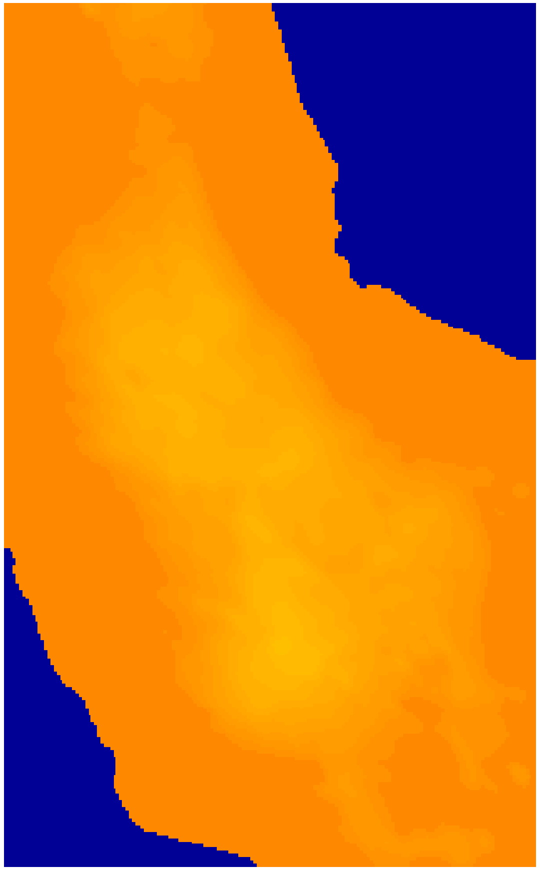
Simulations…



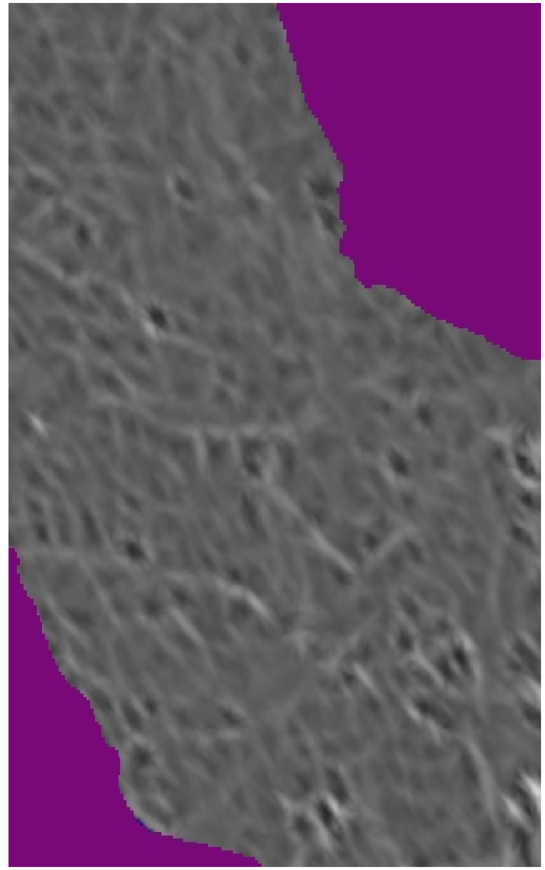
Comparison of field-scale migration with and without faults



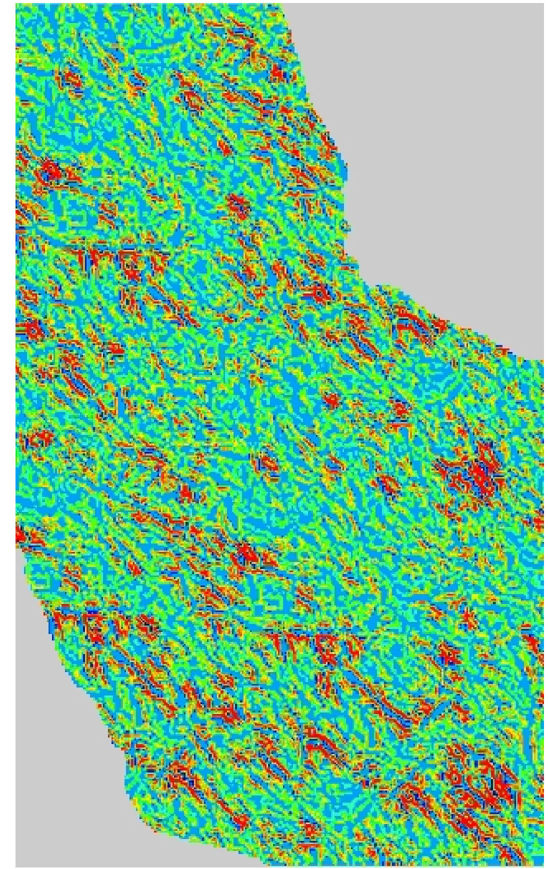
Fracture Model



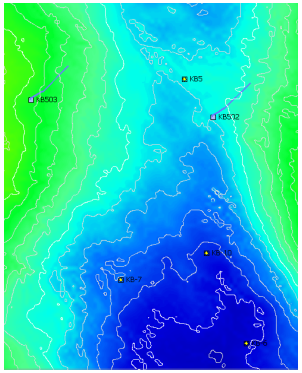
Map input

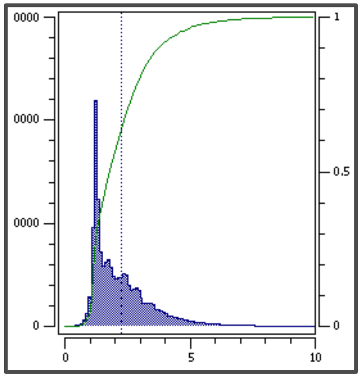


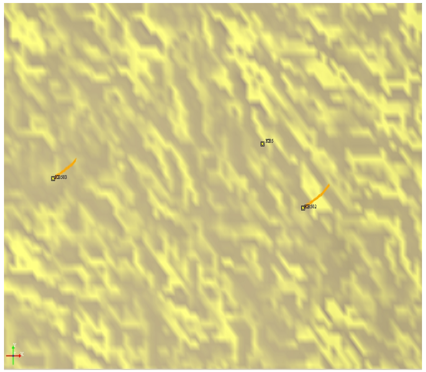
Curvature Analysis

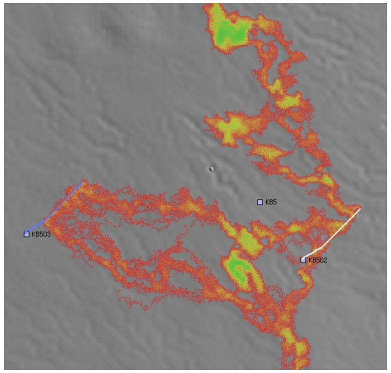


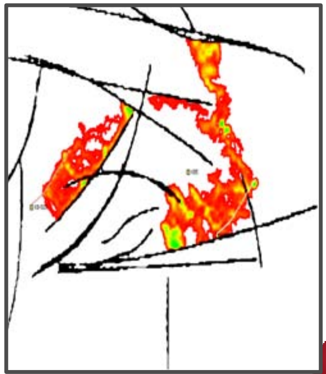
Edge Detection











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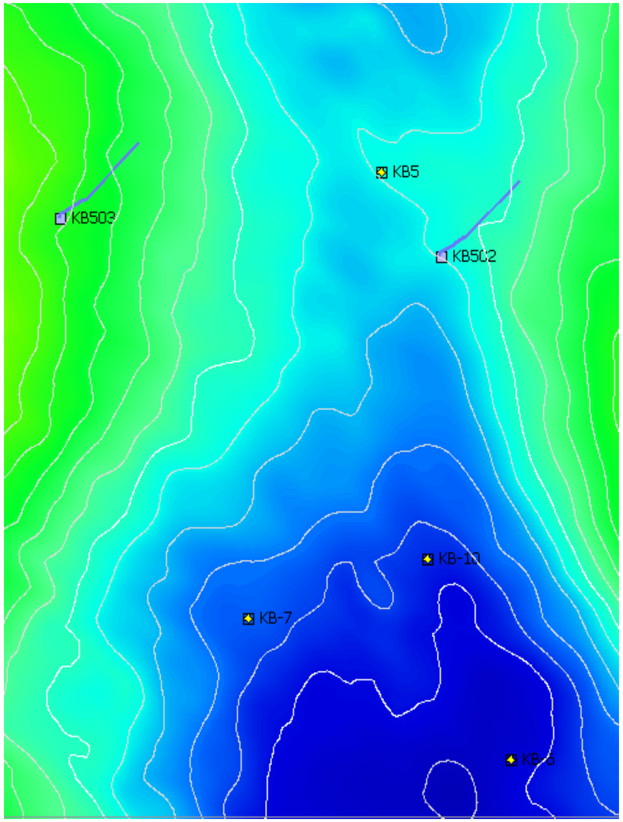
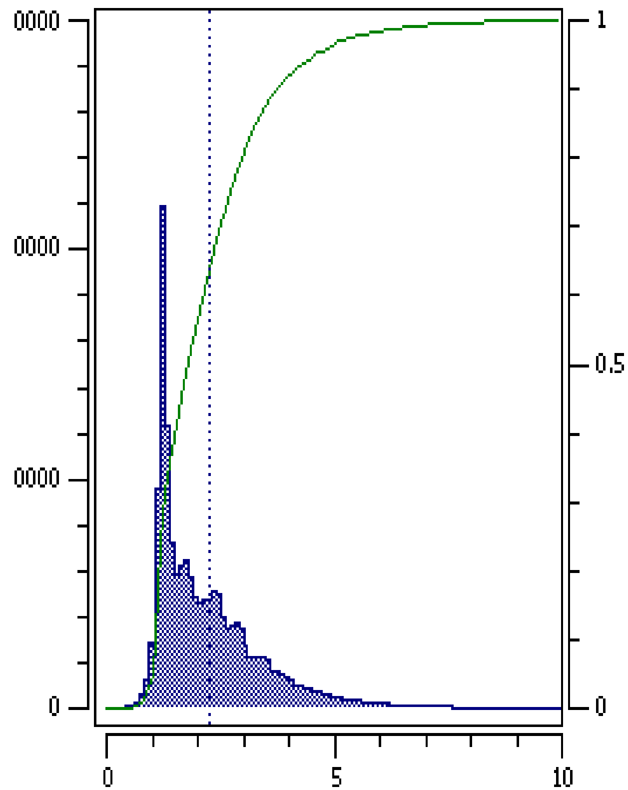
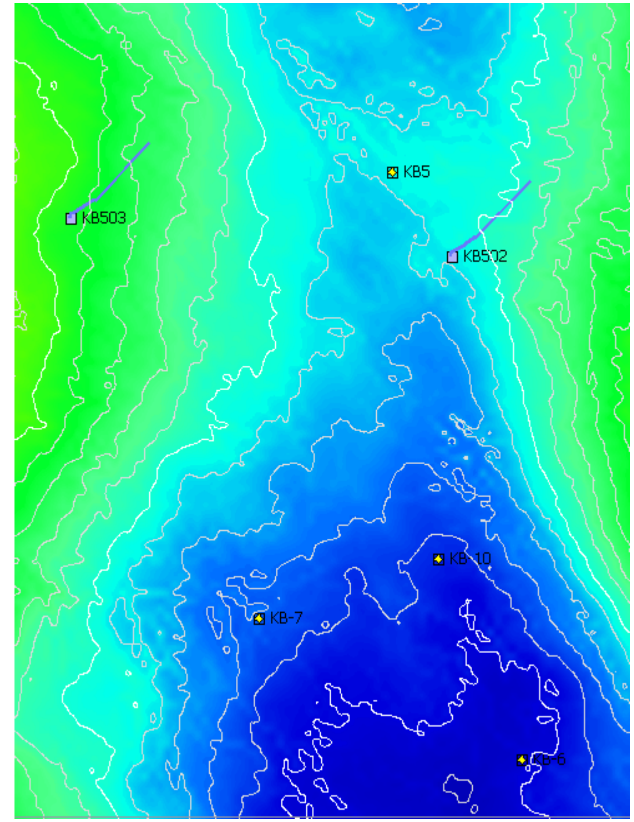


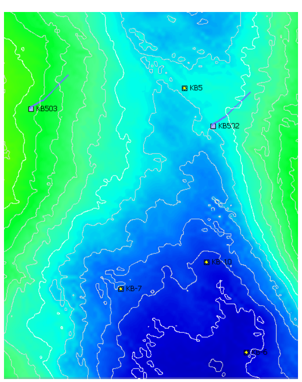
Northern area contour map

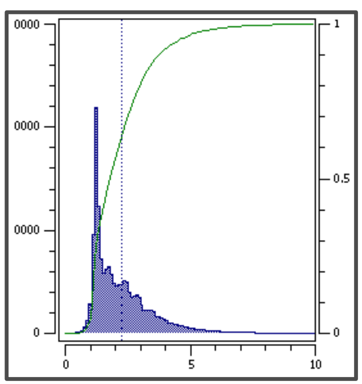


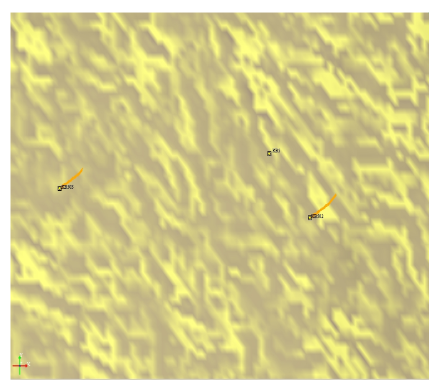
Log-normal fracture distribution

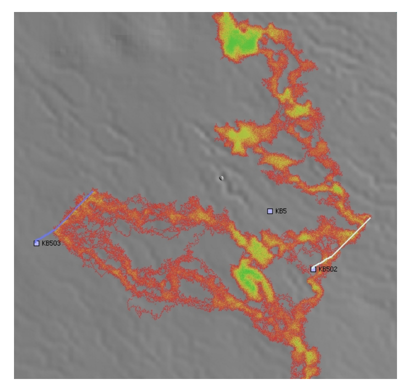


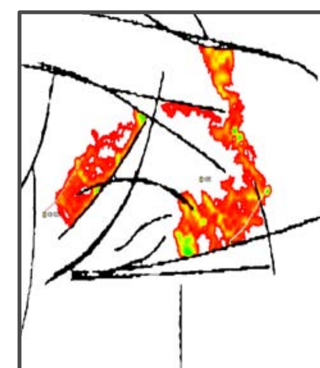
Contour map after fabric added





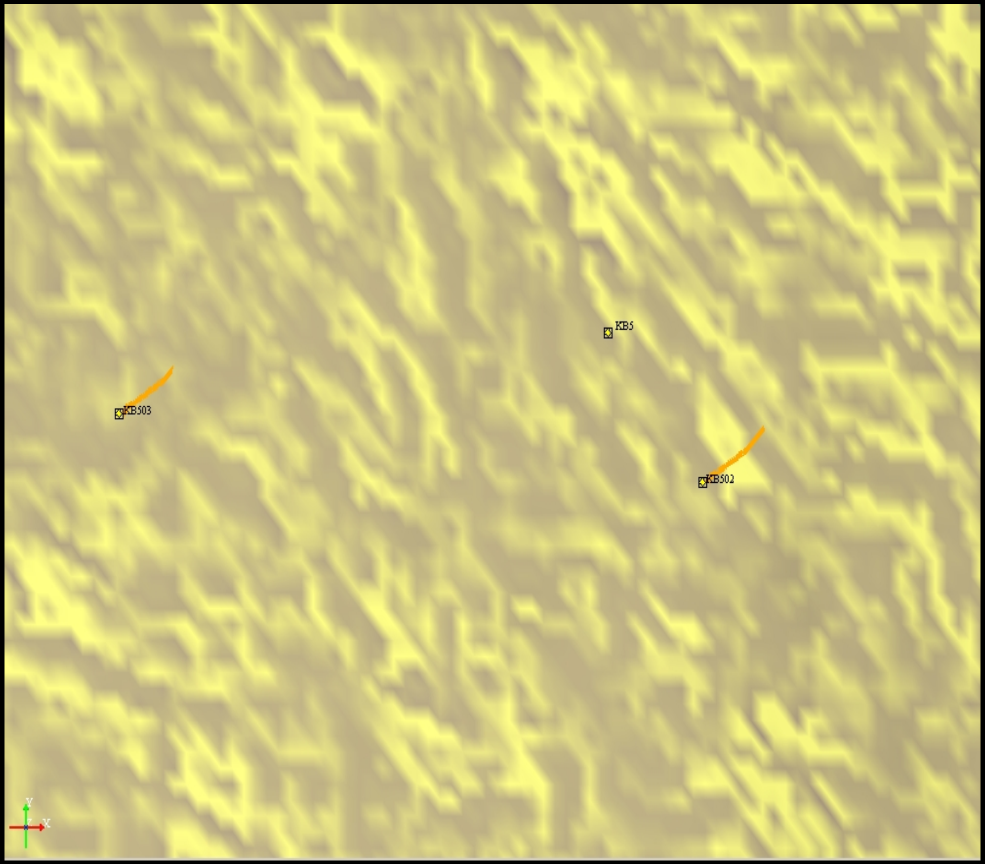




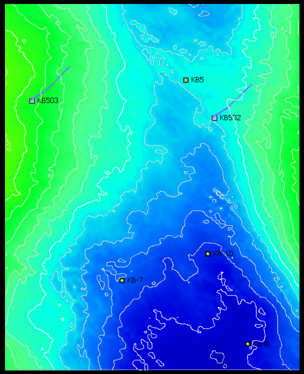


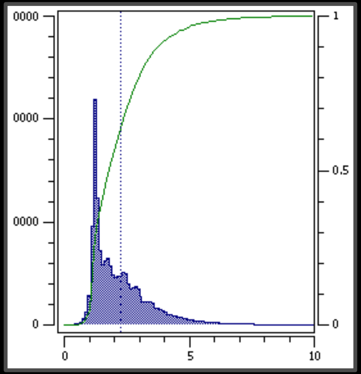
Simulations…

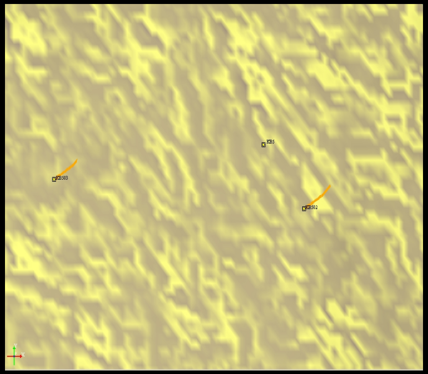
Migration with Fractures

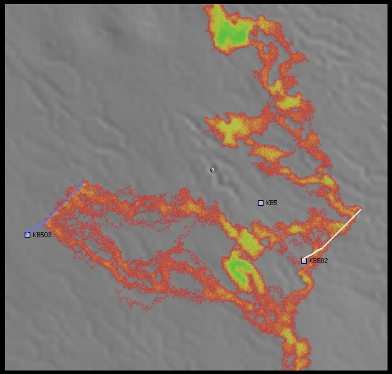


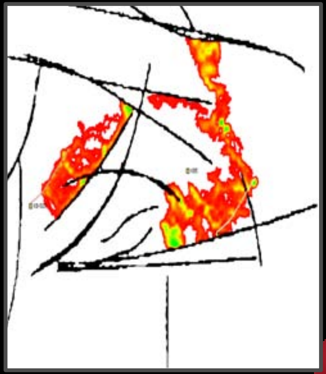
Reservoir with fabric added





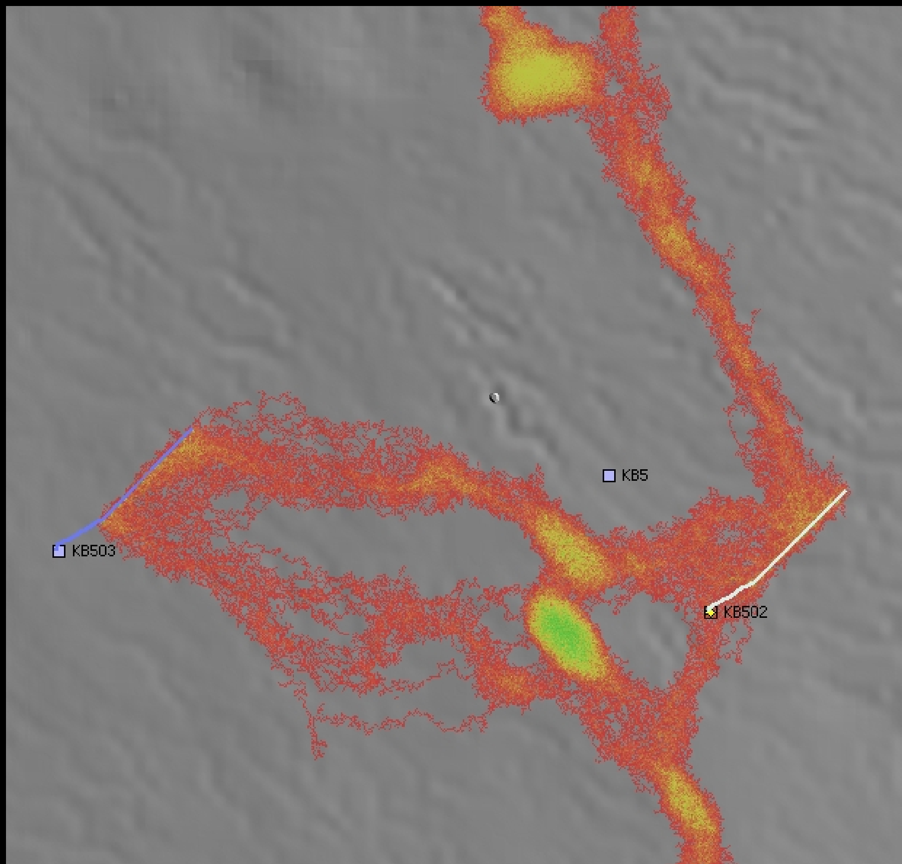






Simulations…

Migration with Fractures



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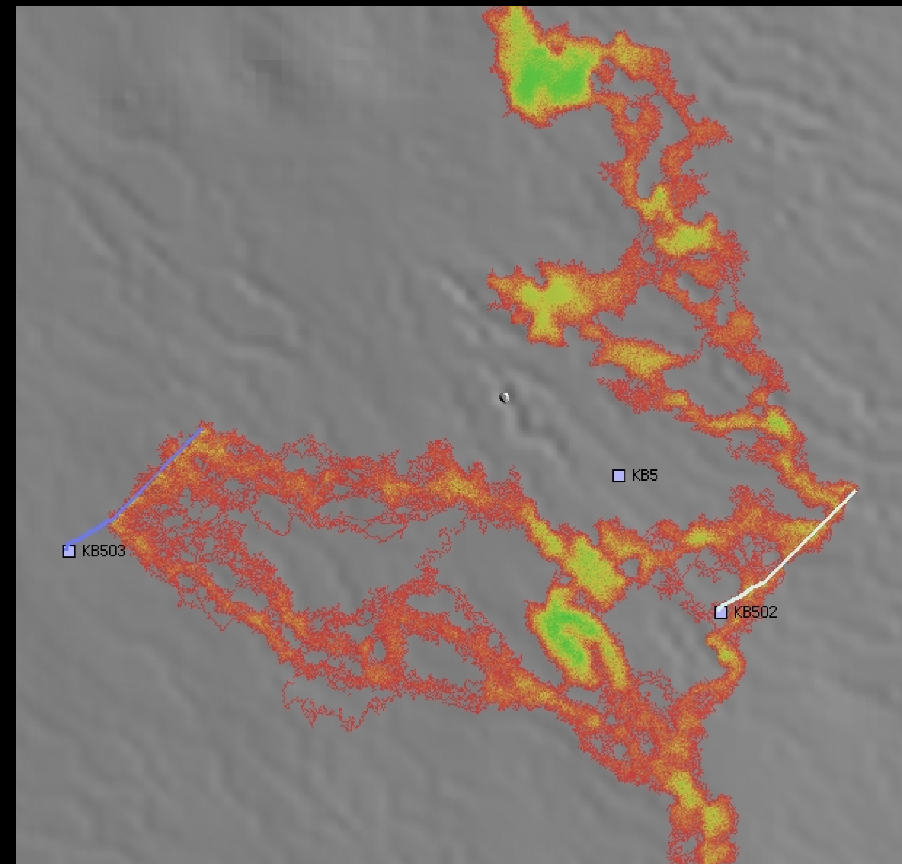

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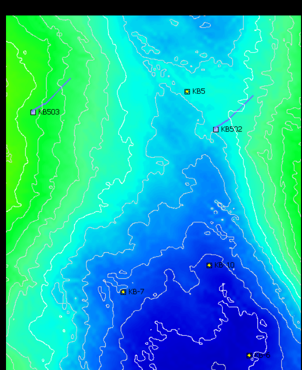
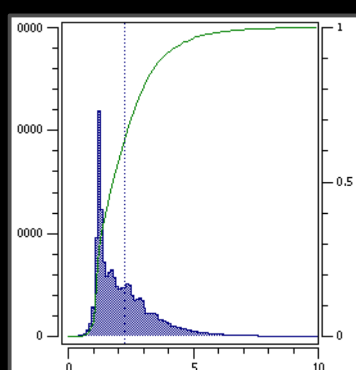
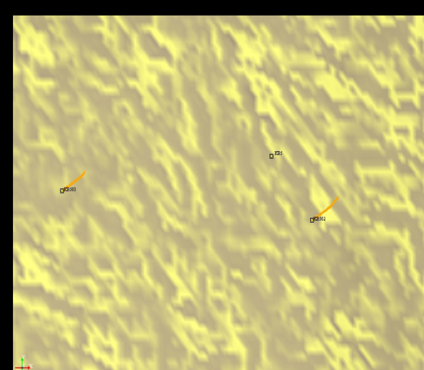
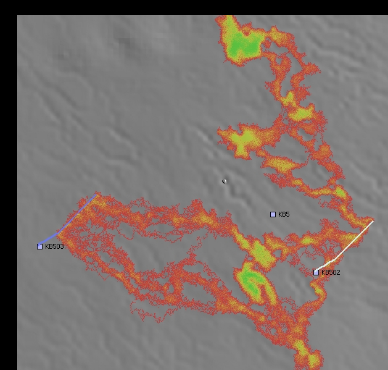
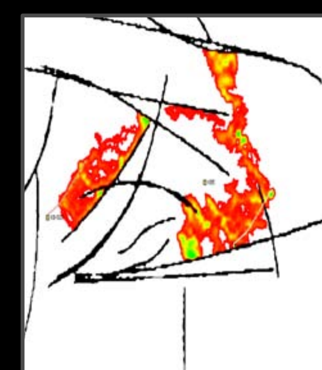


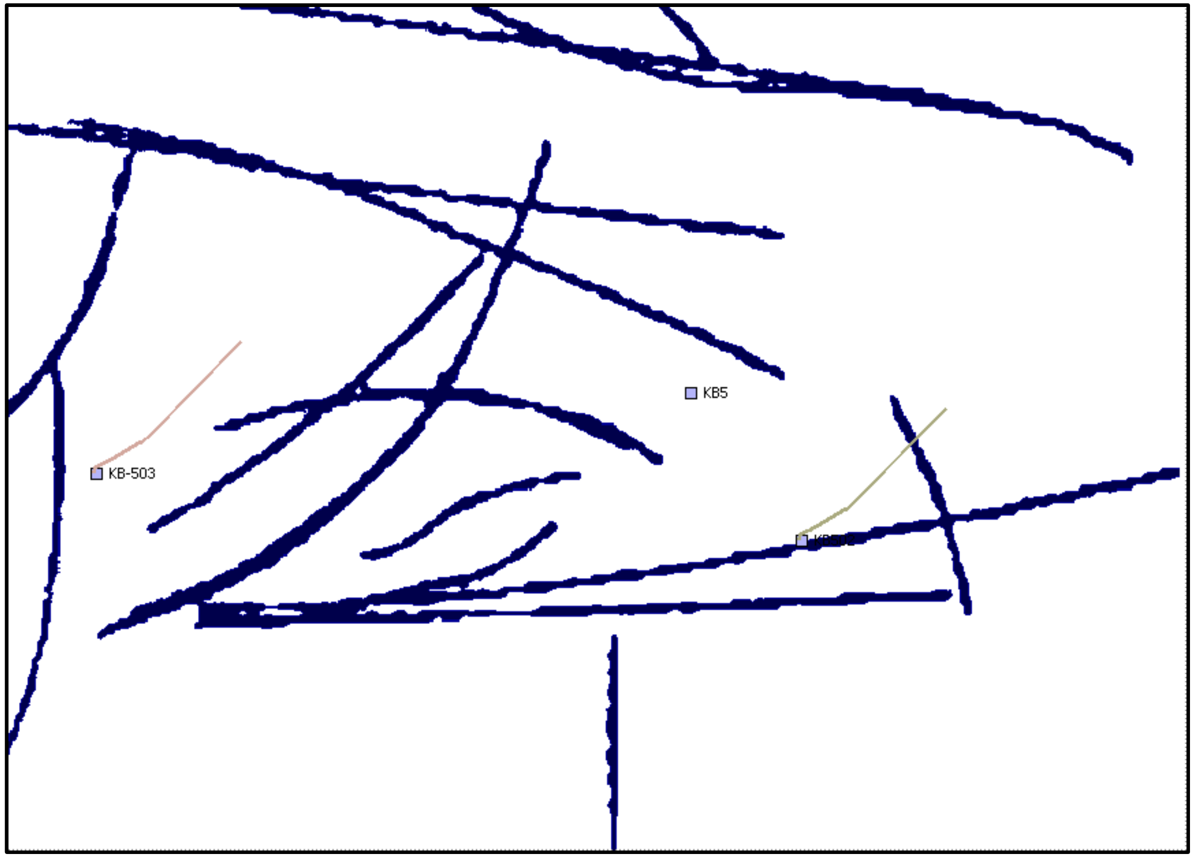






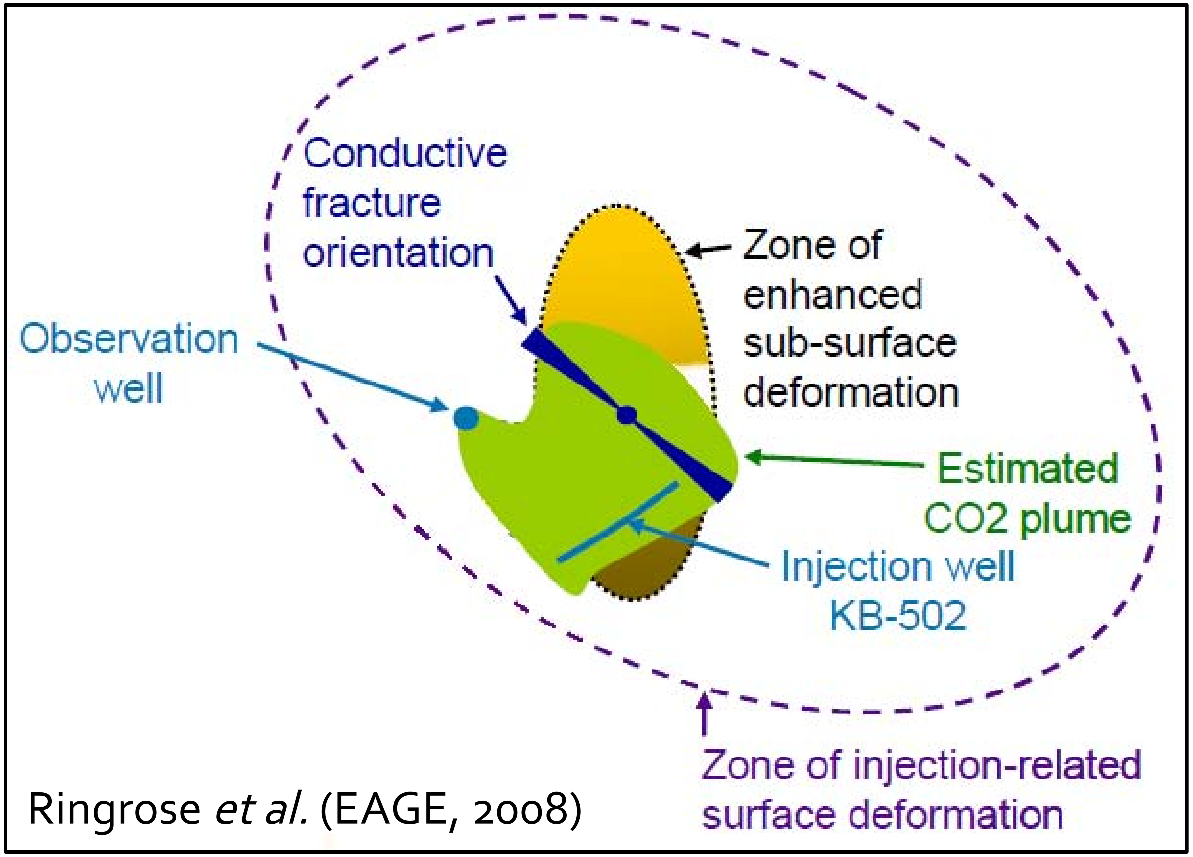


Comparison to Observations



Northern Area early filling sequence

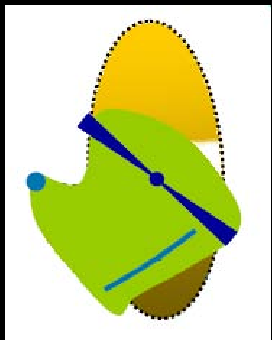
Comparison to Observations

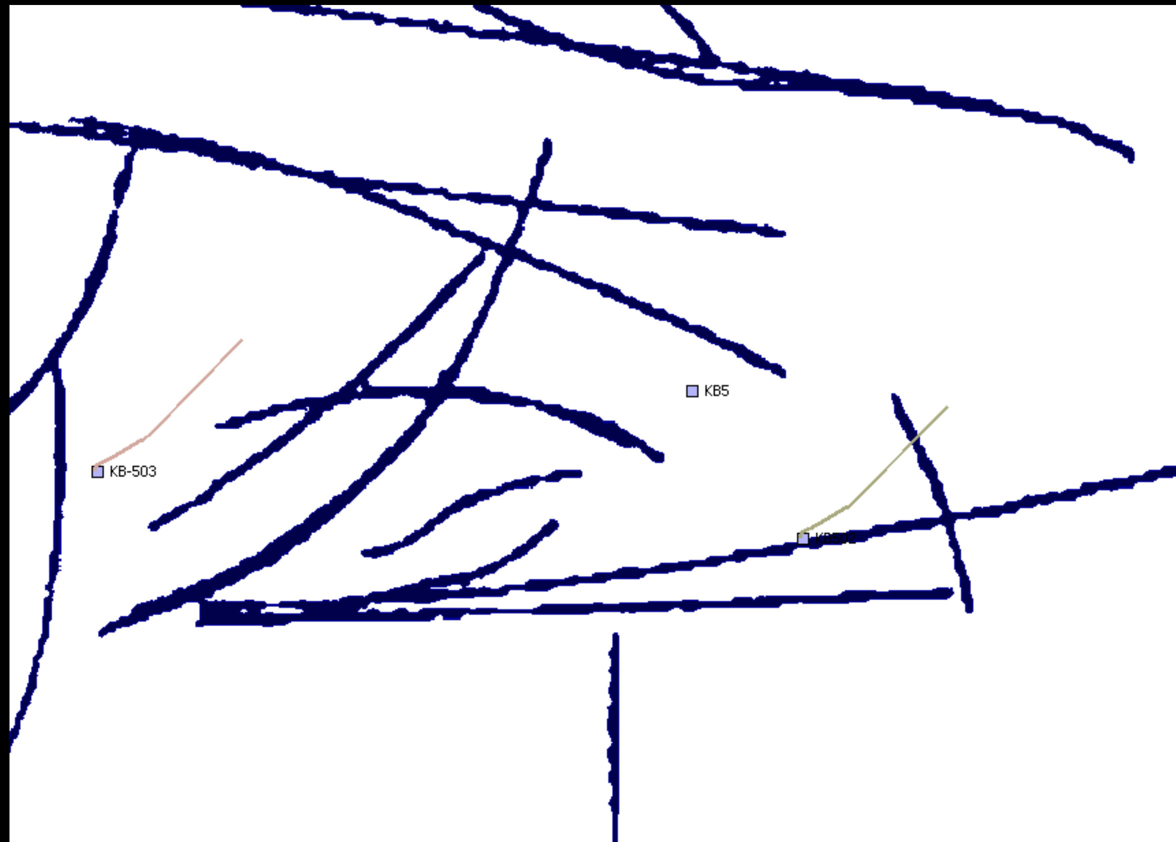


Ringrose *et al.* (EAGE, 2008)

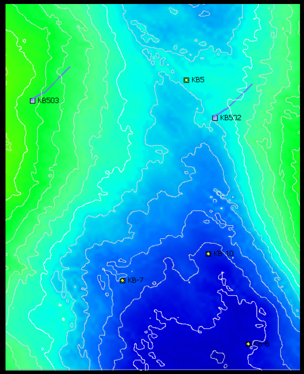
Northern Area early filling sequence

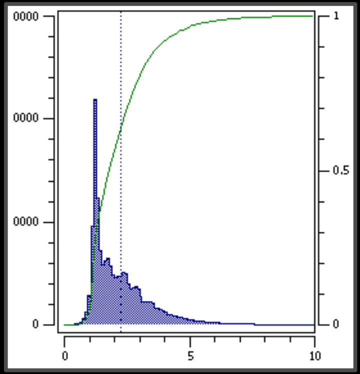
Simulations…

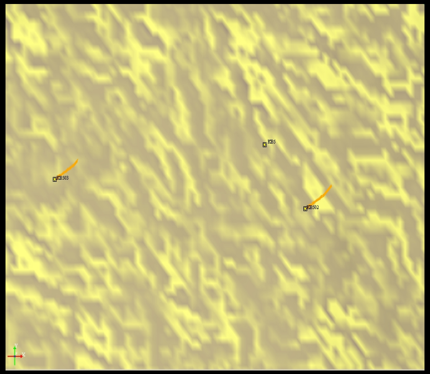


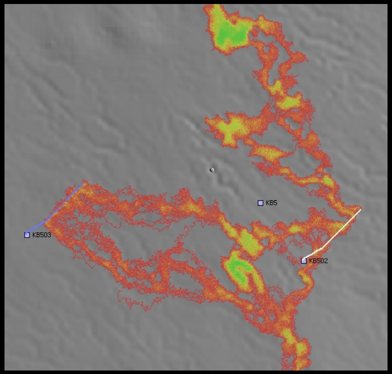


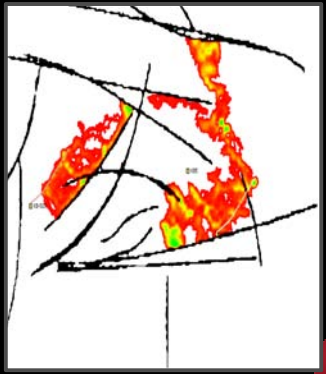
Northern Area early filling sequence (N=20)











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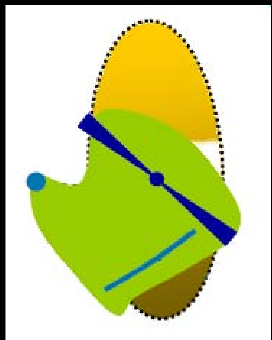
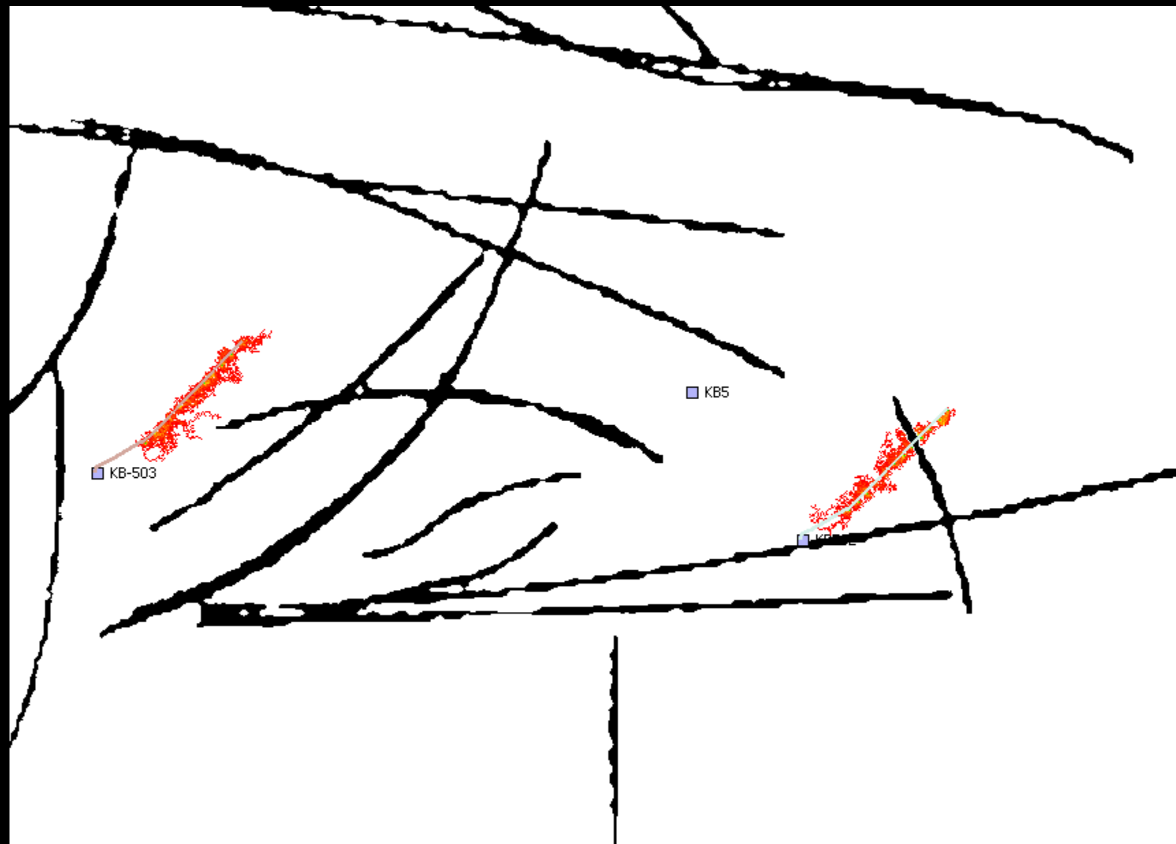
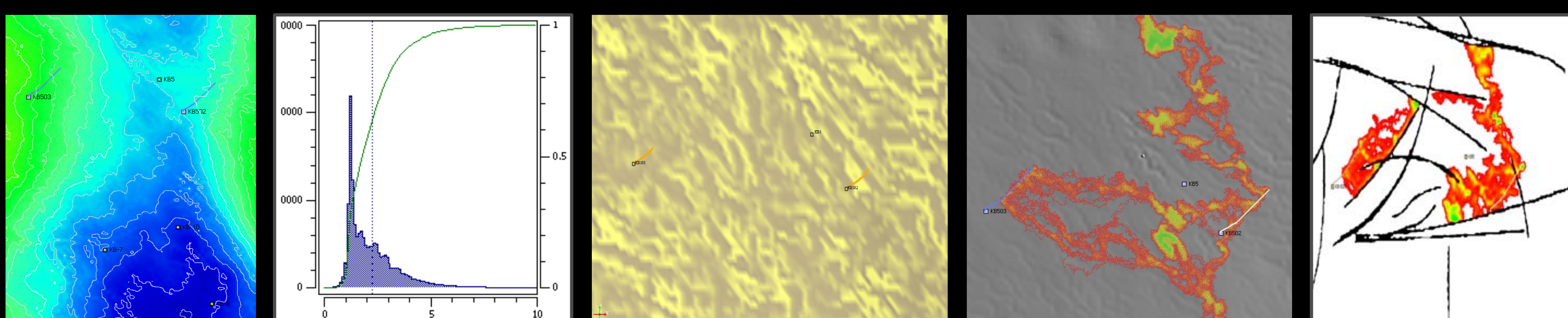




Northern Area early filling sequence (N=20)



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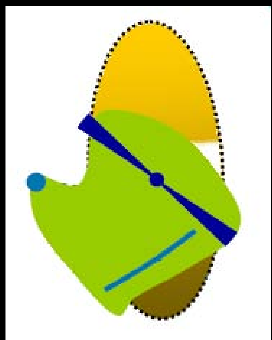

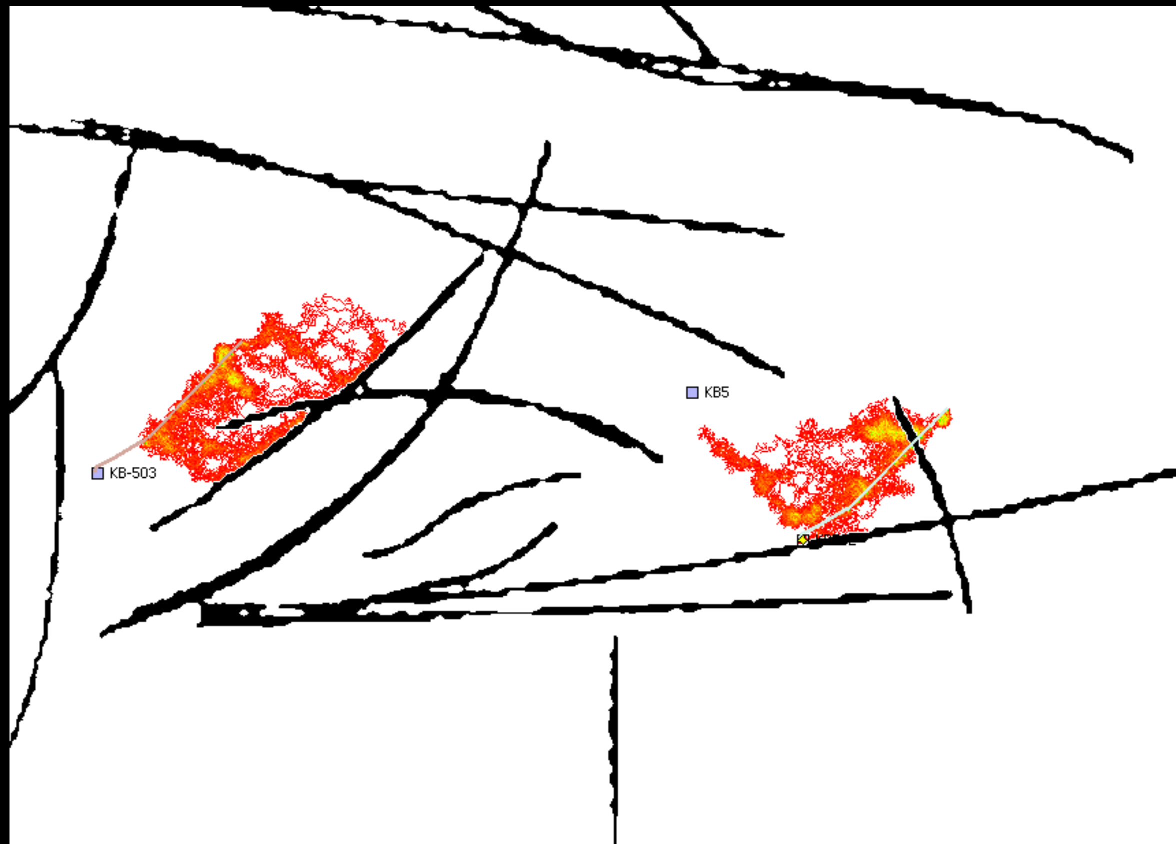

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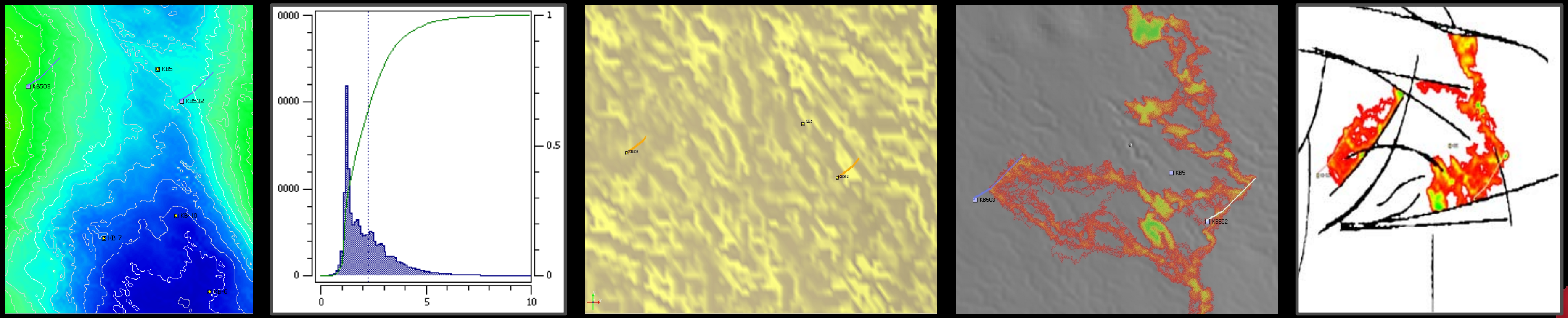

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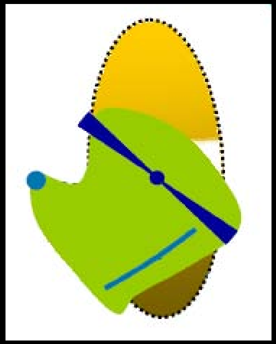

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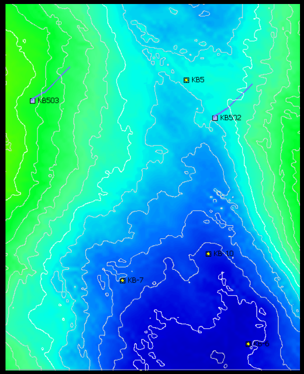

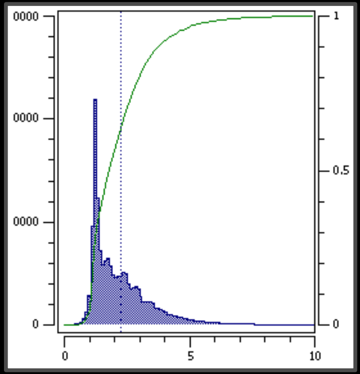

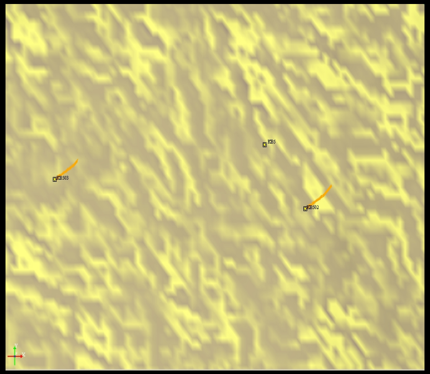

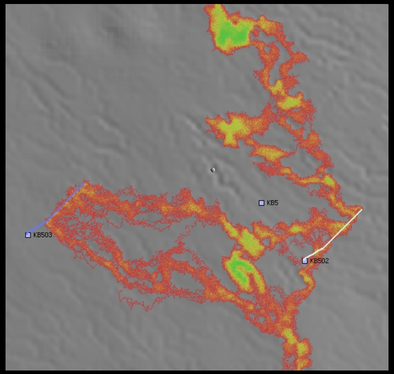

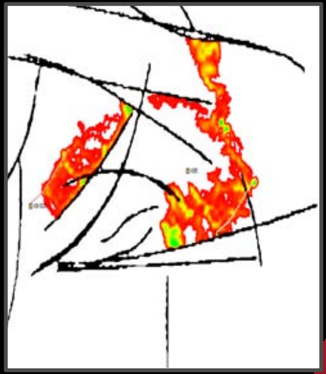

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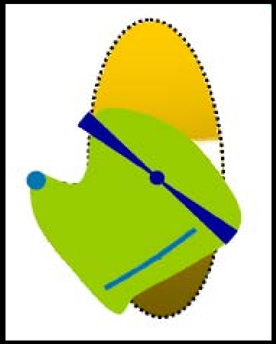
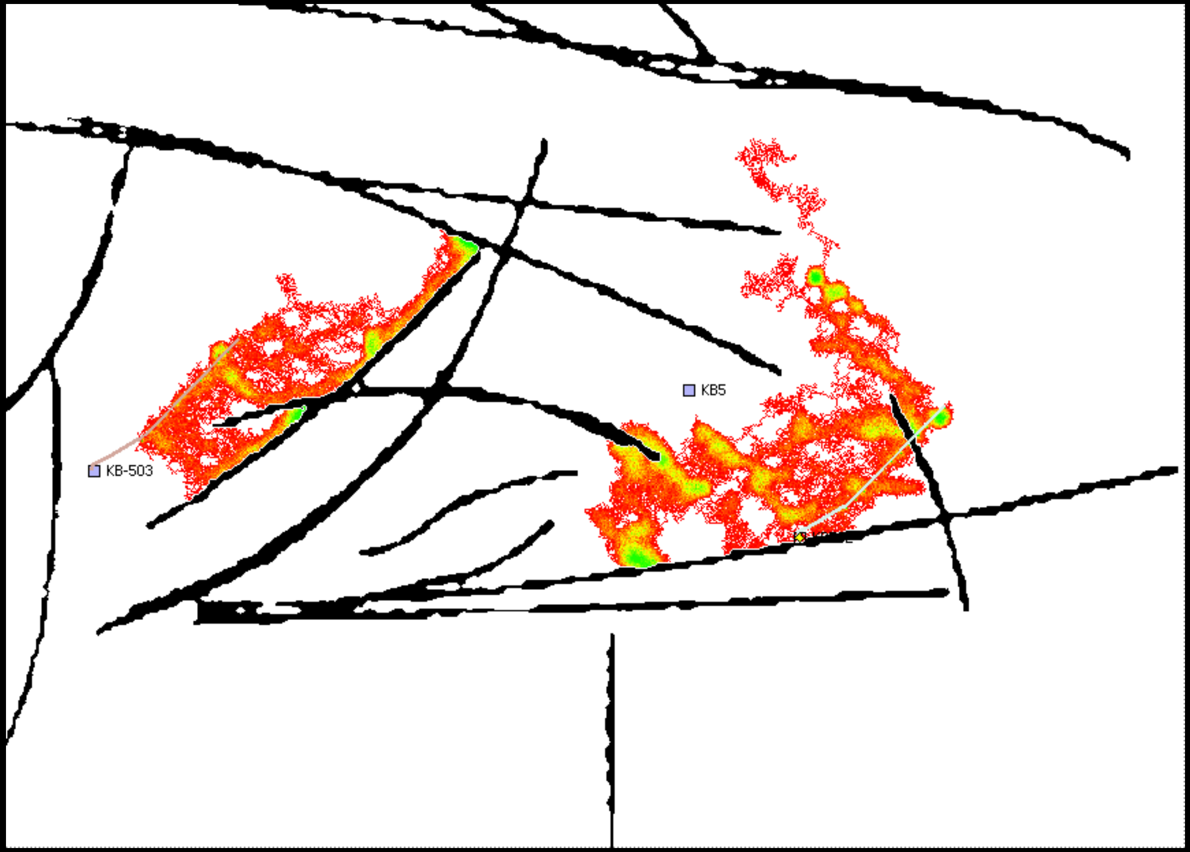
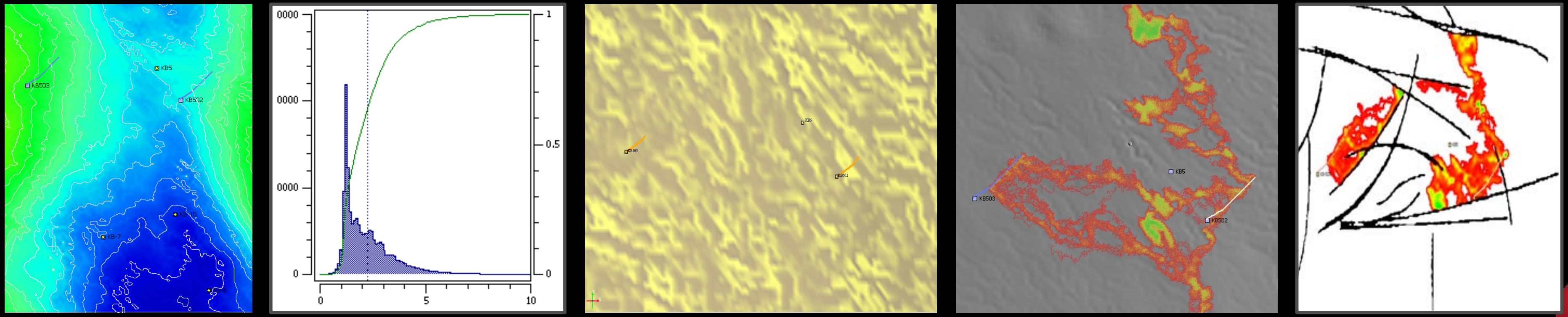




Northern Area early filling sequence (N=20)



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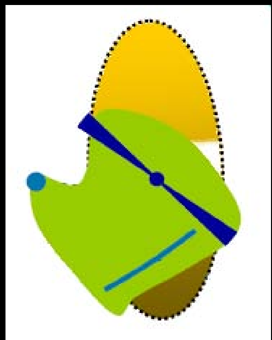

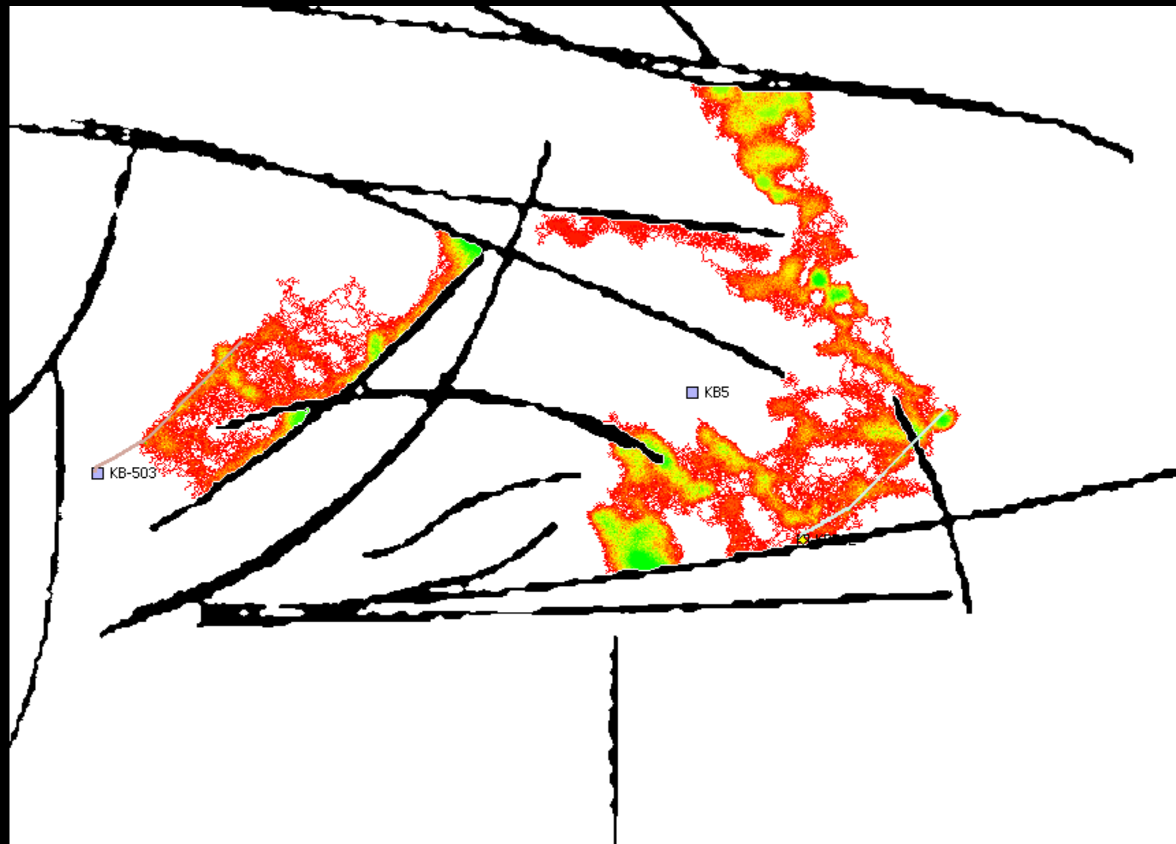

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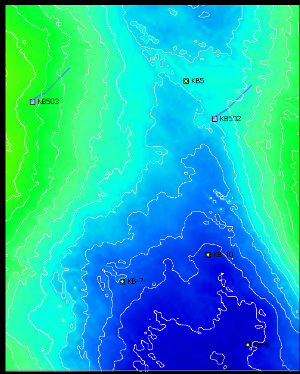

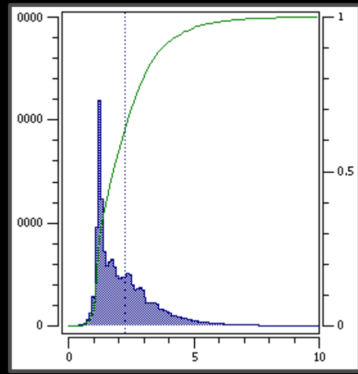

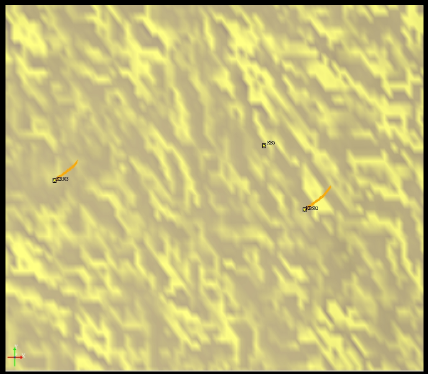

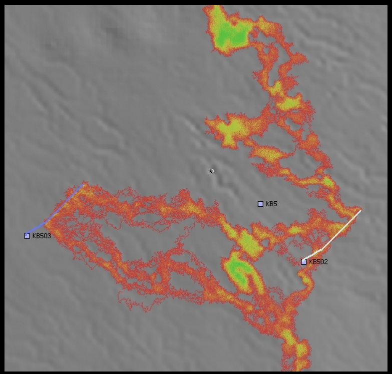

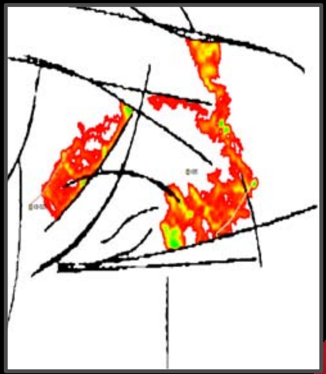

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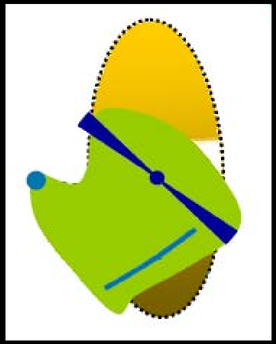
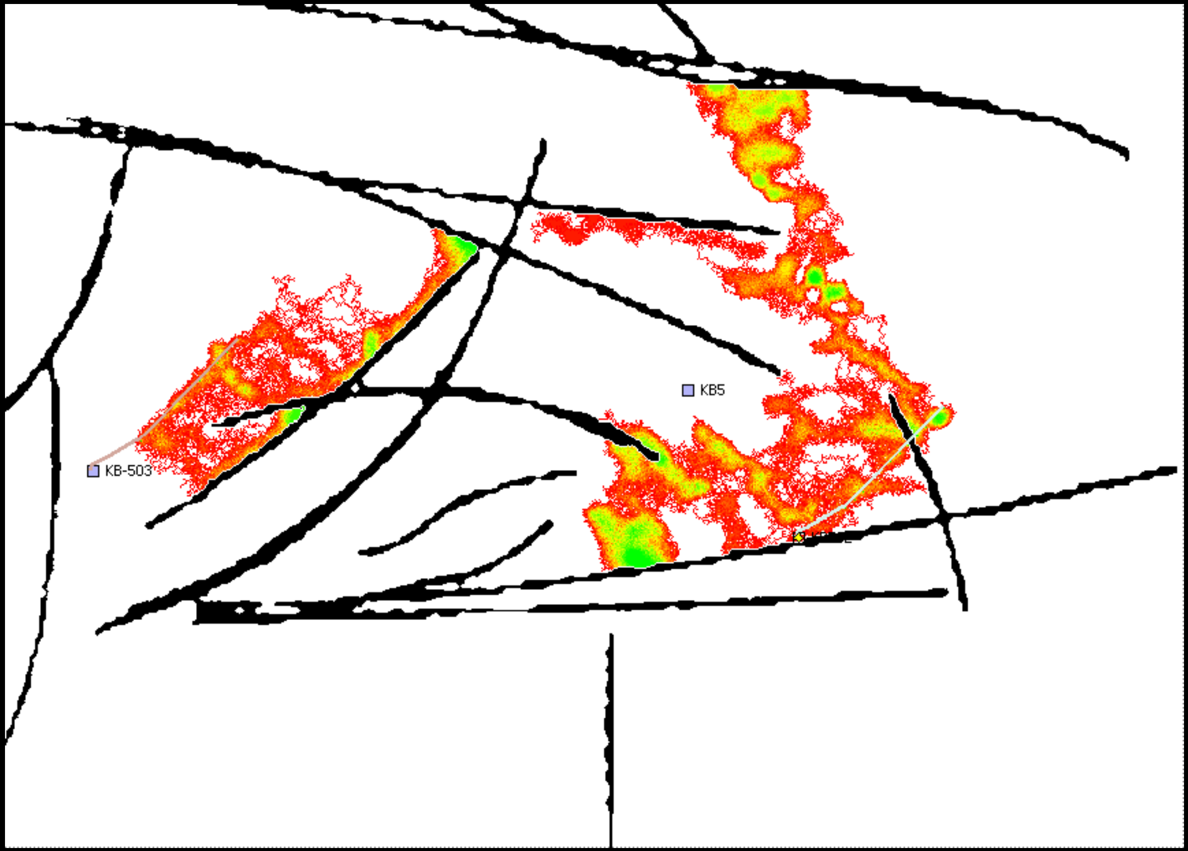
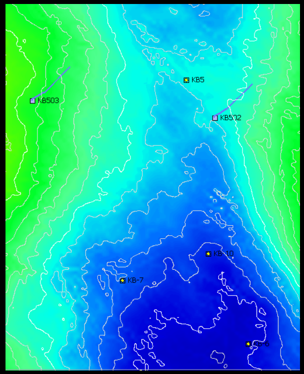
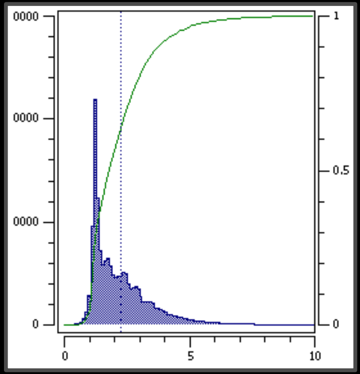
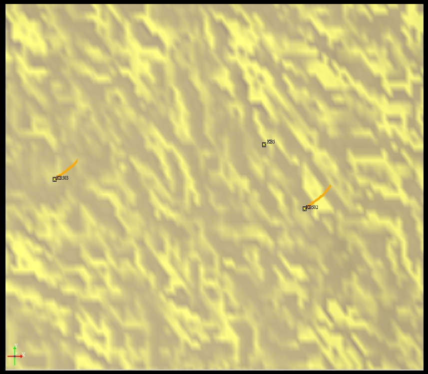


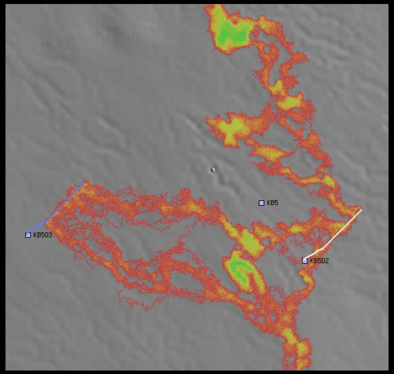


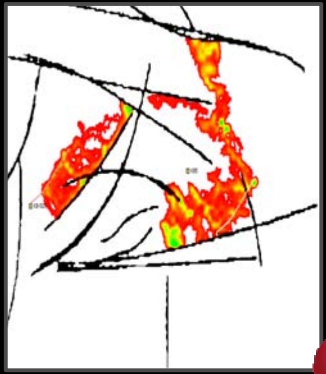
Northern Area early filling sequence (N=20)



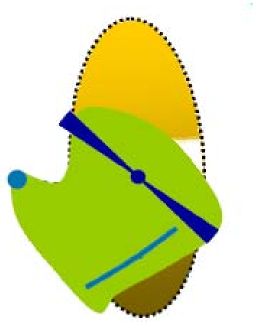




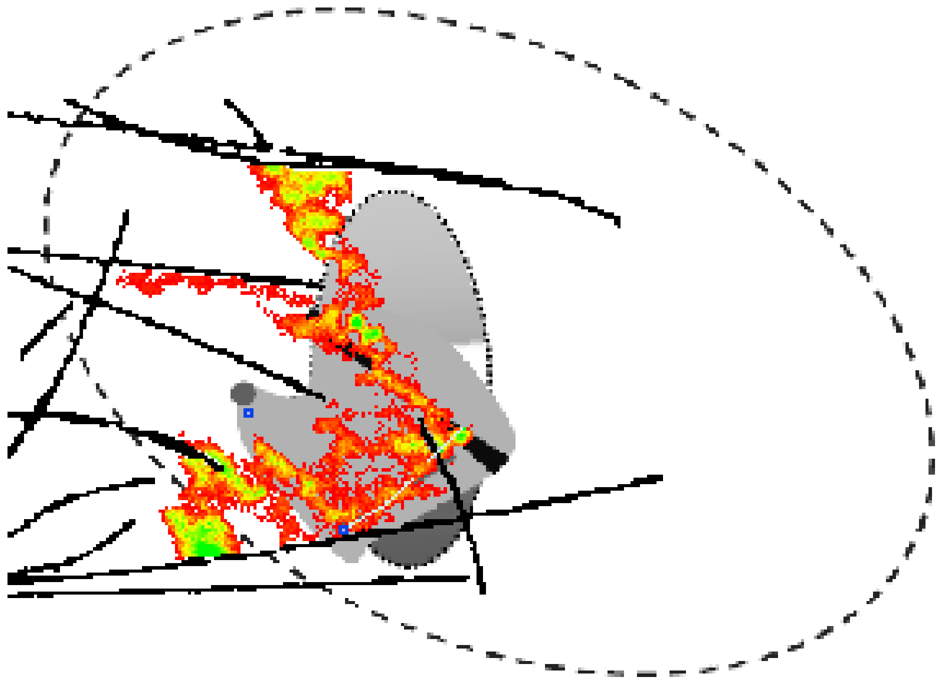




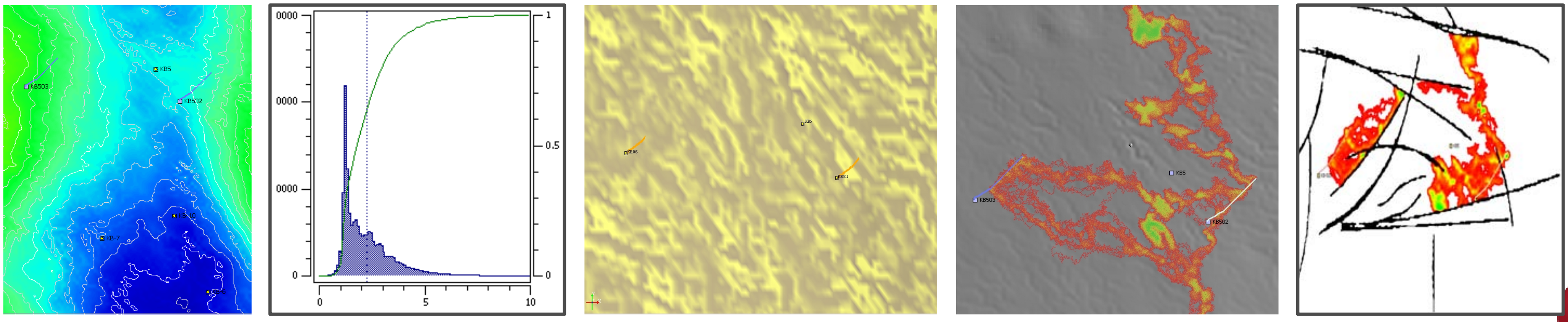
Comparison to Observations



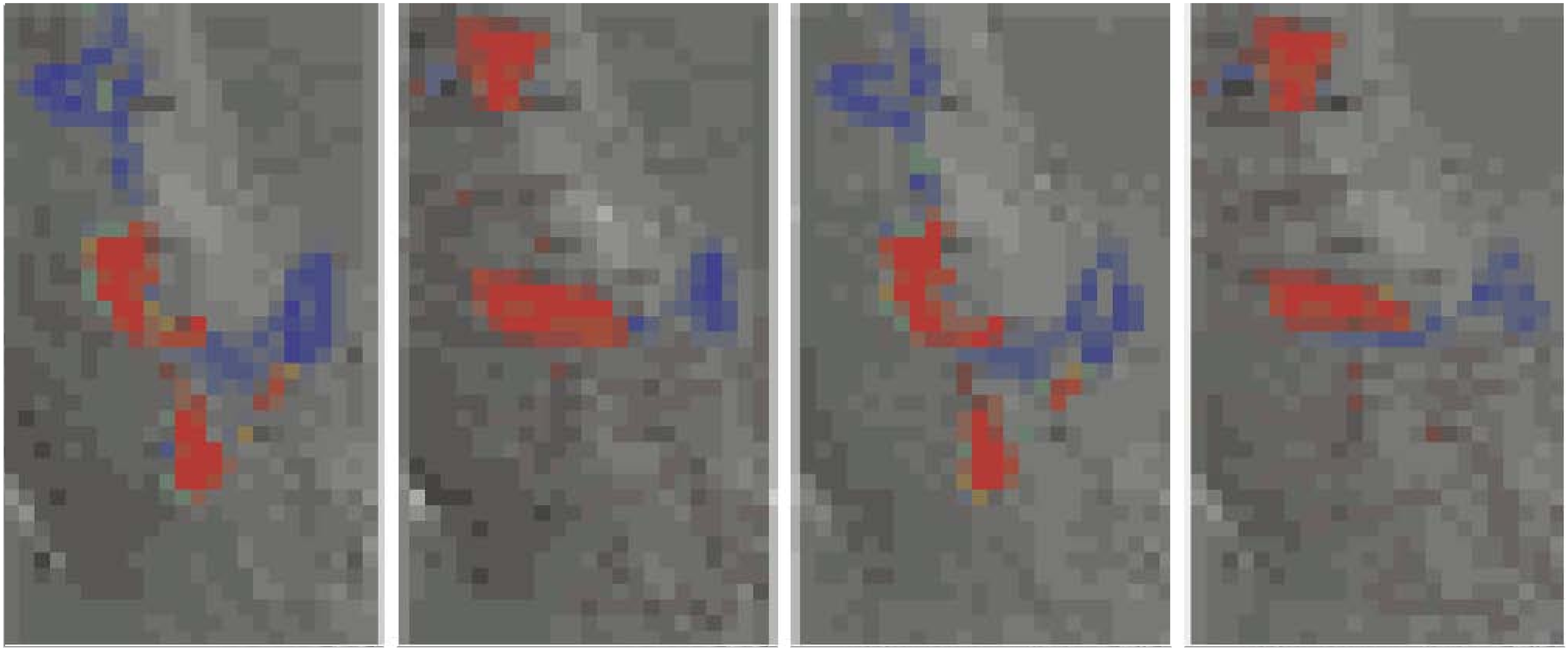
Ringrose *et al.*
(EAGE, 2009)



Match to expected CO_2 distribution

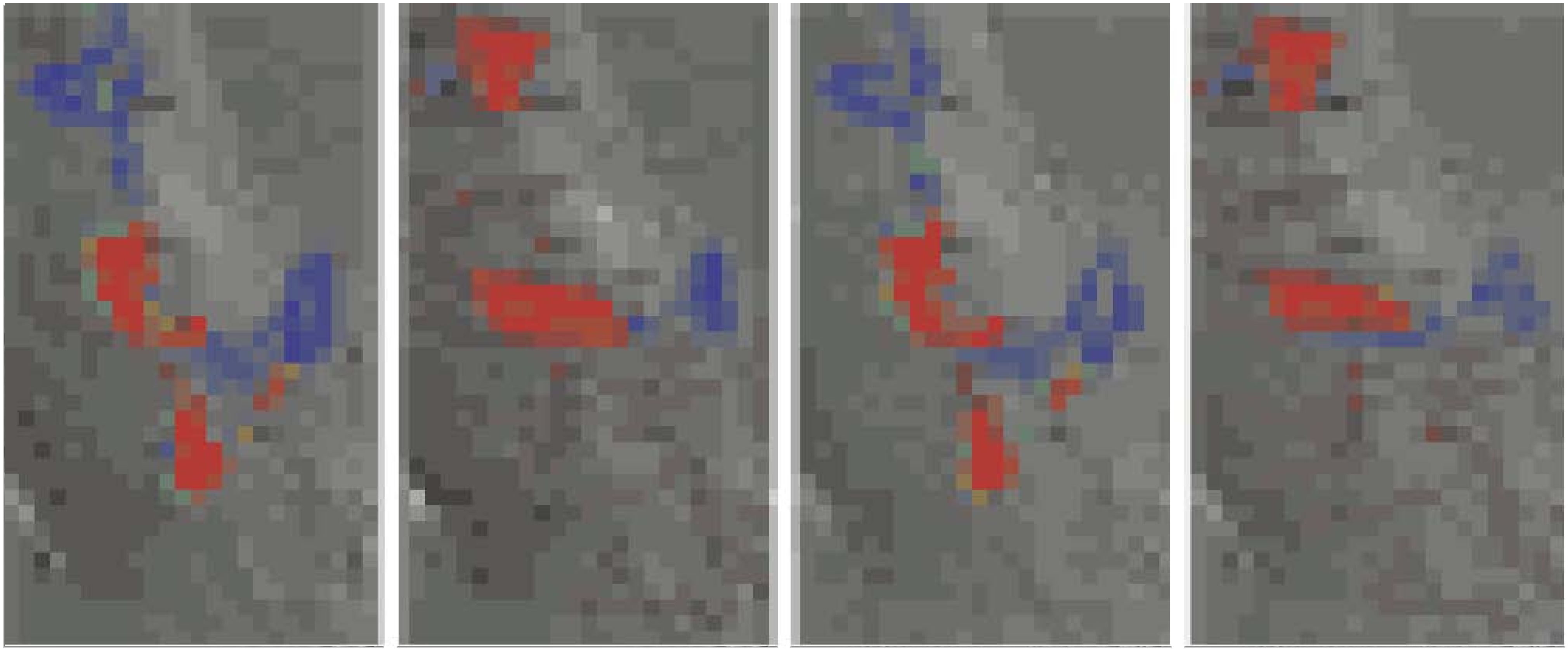


Conclusion



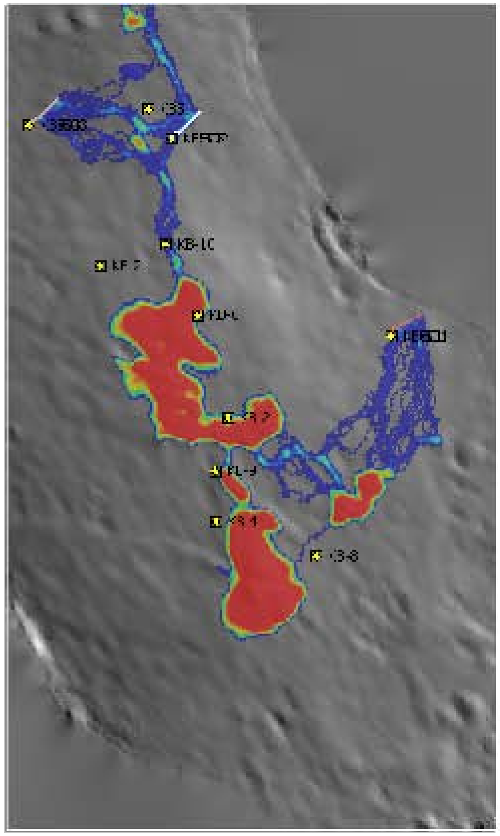
Topography Faults Fractures Fractured and Faulted

Conclusion: why model at low resolution?

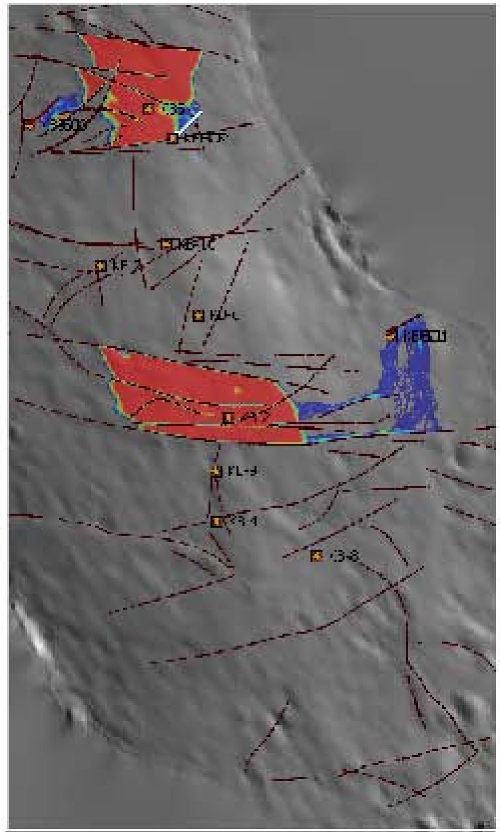


Topography Faults Fractures Fractured and Faulted

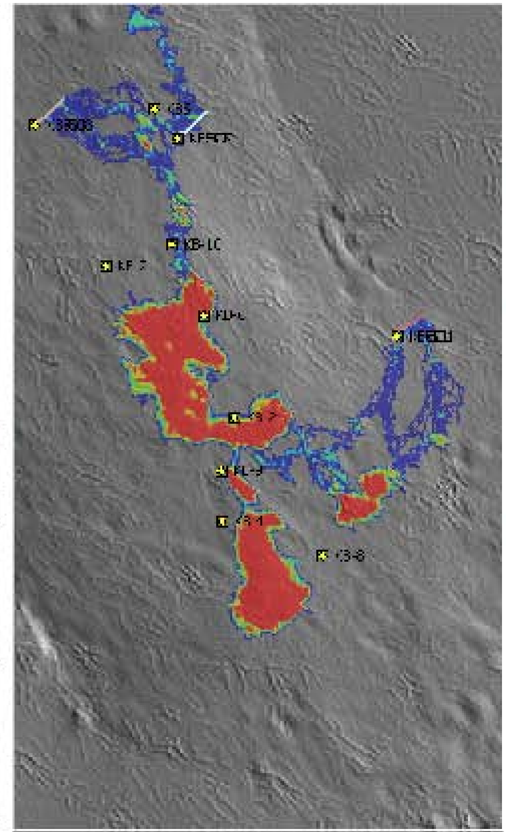
Conclusion: why model at low resolution…



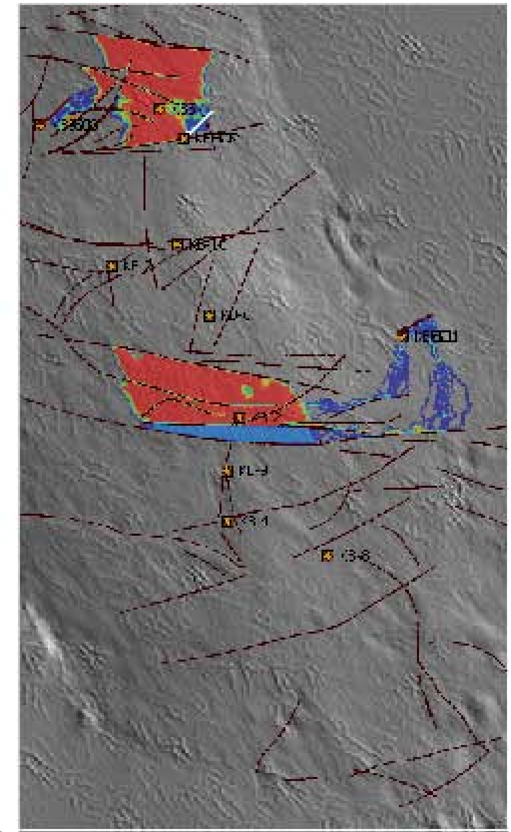
Topography



Faults



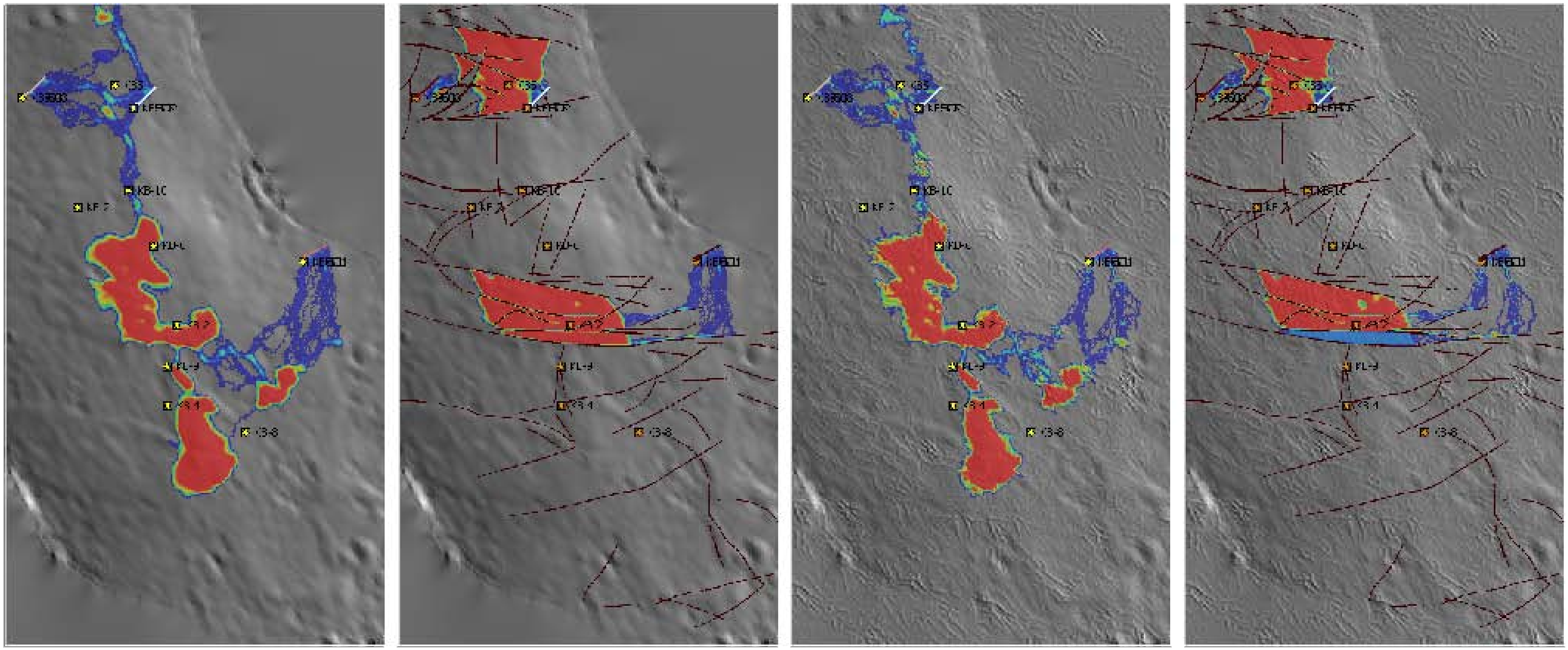
Fractures



Fractured and Faulted

…when heterogeneity matters?

Conclusion: why model at low resolution…



Topography | Faults | Fractures | Fractured and Faulted

…when heterogeneity matters?

umbers Capillary Numbers Capillary Numbers Capillary Numbers Capillary numbers

References

- AAPG Memoir 85: Faults, Fluid Flow and Petroleum Traps (2005)
- AAPG Hedberg Series 2: Evaluating Fault and Caprock Seals (2005)

Empirical Relationships

- Yang & Aplin (2009)
- Sorkhabi & Tsuji (2005)
- Poelchau *et al*. (1997)

The In Salah Project

- Ringrose *et al., First Break* (2009)
- Iding & Ringrose, *Energy Procedia* (2009)
- Foster *et al., Journees Scientifiques et Techniques* (2004)

Fault Leakage

- Manzocchi *et al.,* Petroleum Geoscience (1998-2008)
- Hermanrud *et al.,* AAPG Hedberg Series 2 (2005)

Invasion Percolation

- Carruthers (2003)
- Meakin *et al.* (2000)
- Boettcher *et al.* (2002)
- England *et al.* (1987)

Curvature Analysis

- McGill University Seismic Research Group

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