Improving the recovery factor and profitability of waterflooding by using rate fluctuation analysis and geomechanical modelling

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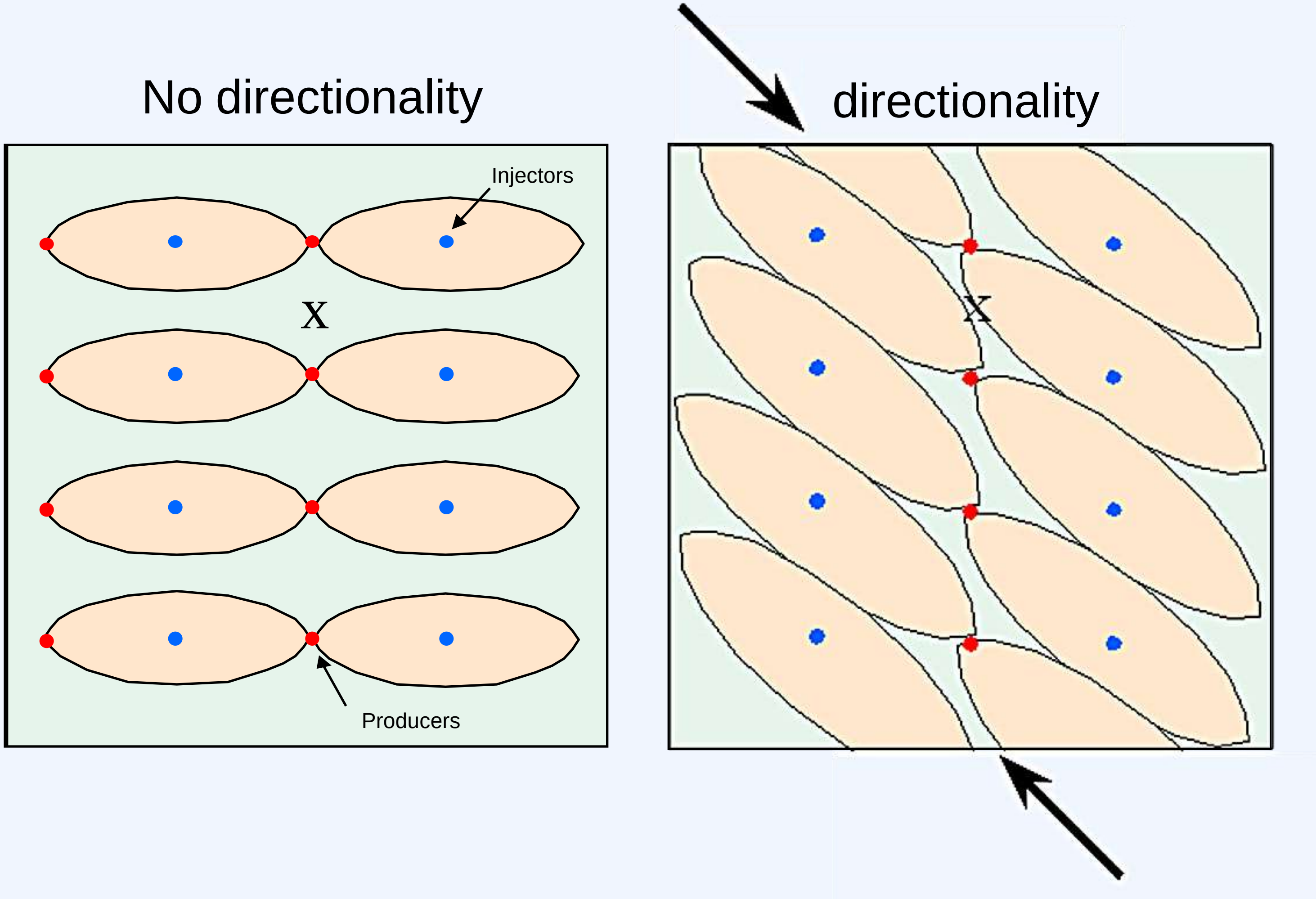
Talk outline

- Reservoir anisotropy and waterflood efficiency
- Rate correlations
  - General characteristics
  - Conceptual mechanisms
- The Statistical Reservoir Model
  - Short-term forecasting
- Rate diffusivities
- Results from 6 North Sea fields
- Integration into reservoir management
- Messages

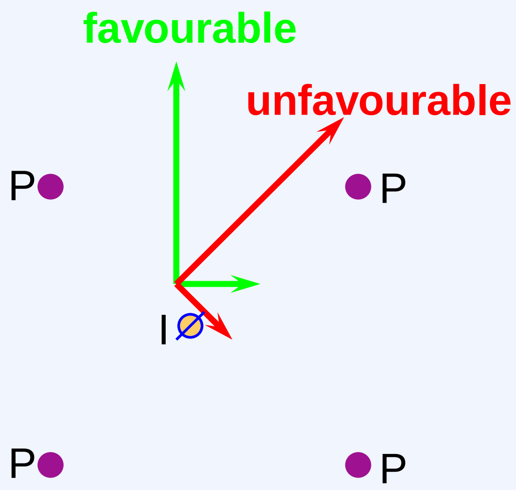
Directionality Impact on Injector Positioning & Infill

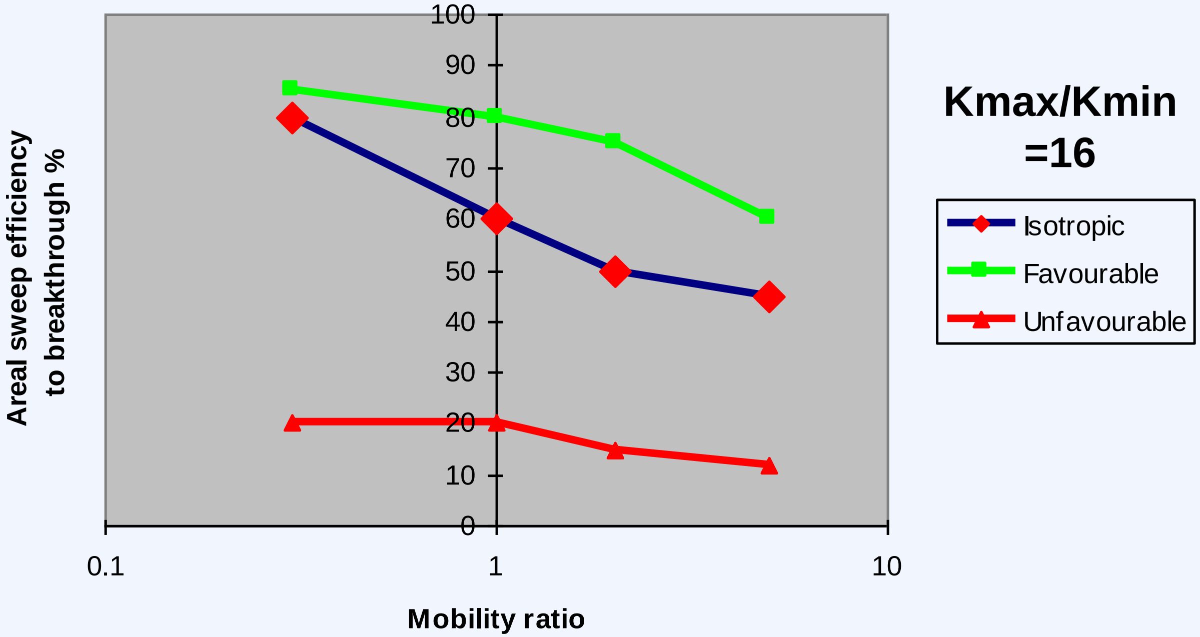


The Prize – theory

Areal sweep efficiency and anisotropic permeability
(classic: Caudle & Loneric 1960)

5 spot pattern

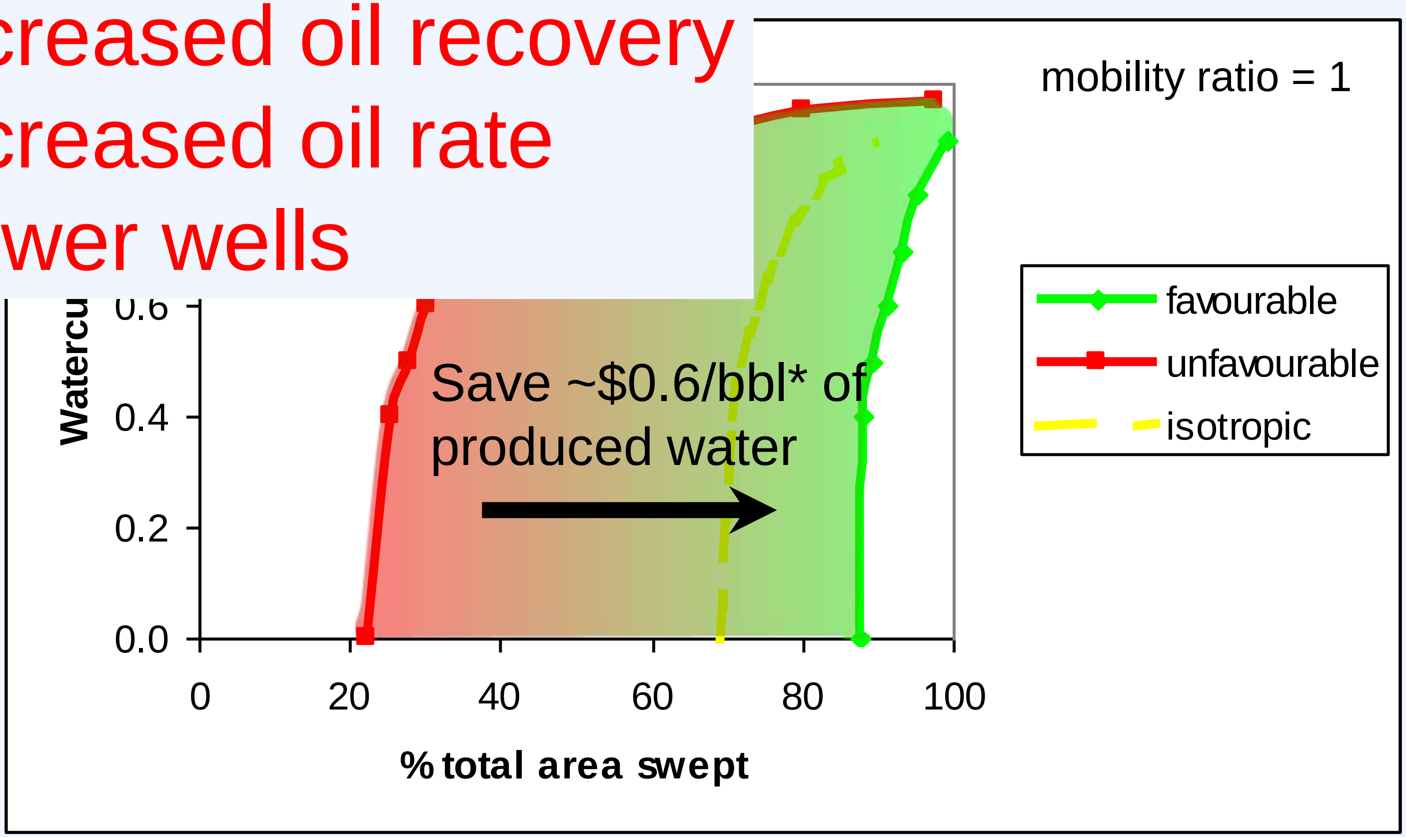




Orientation of well pattern relative to permeability axes can change recovery to breakthrough by 10's of % points

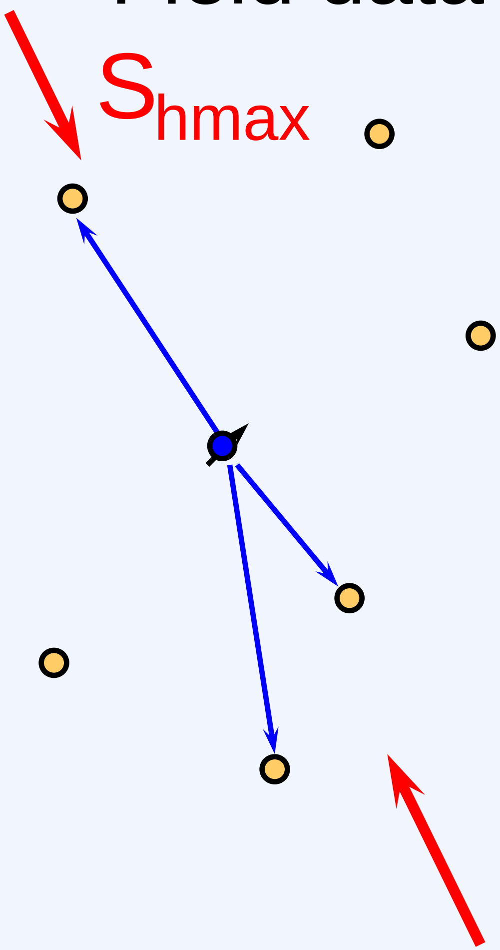
The Prize – theory
Lower watercuts

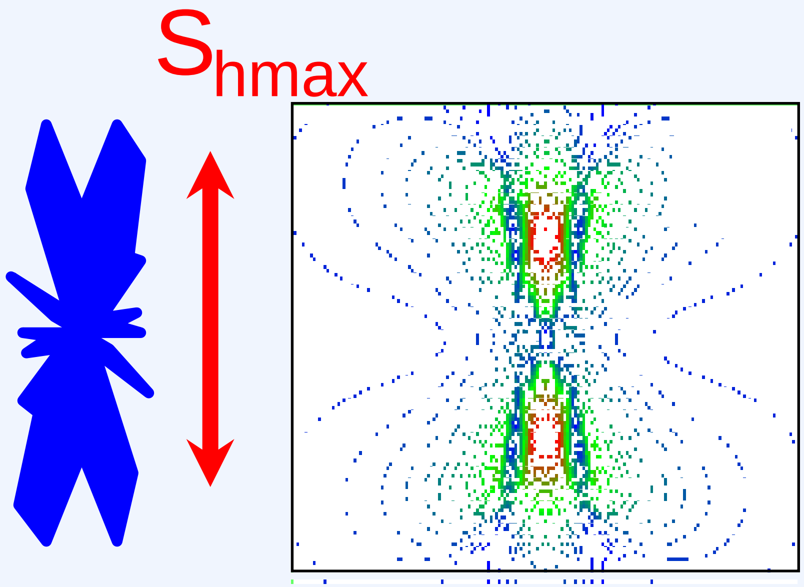
Increased oil recovery
Increased oil rate
Fewer wells



*SPE 73853 Khatib & Vermeek, 2002
e.g. $22million p.a. at 100,000 bwpd

Flood directionality and Stress
Field data

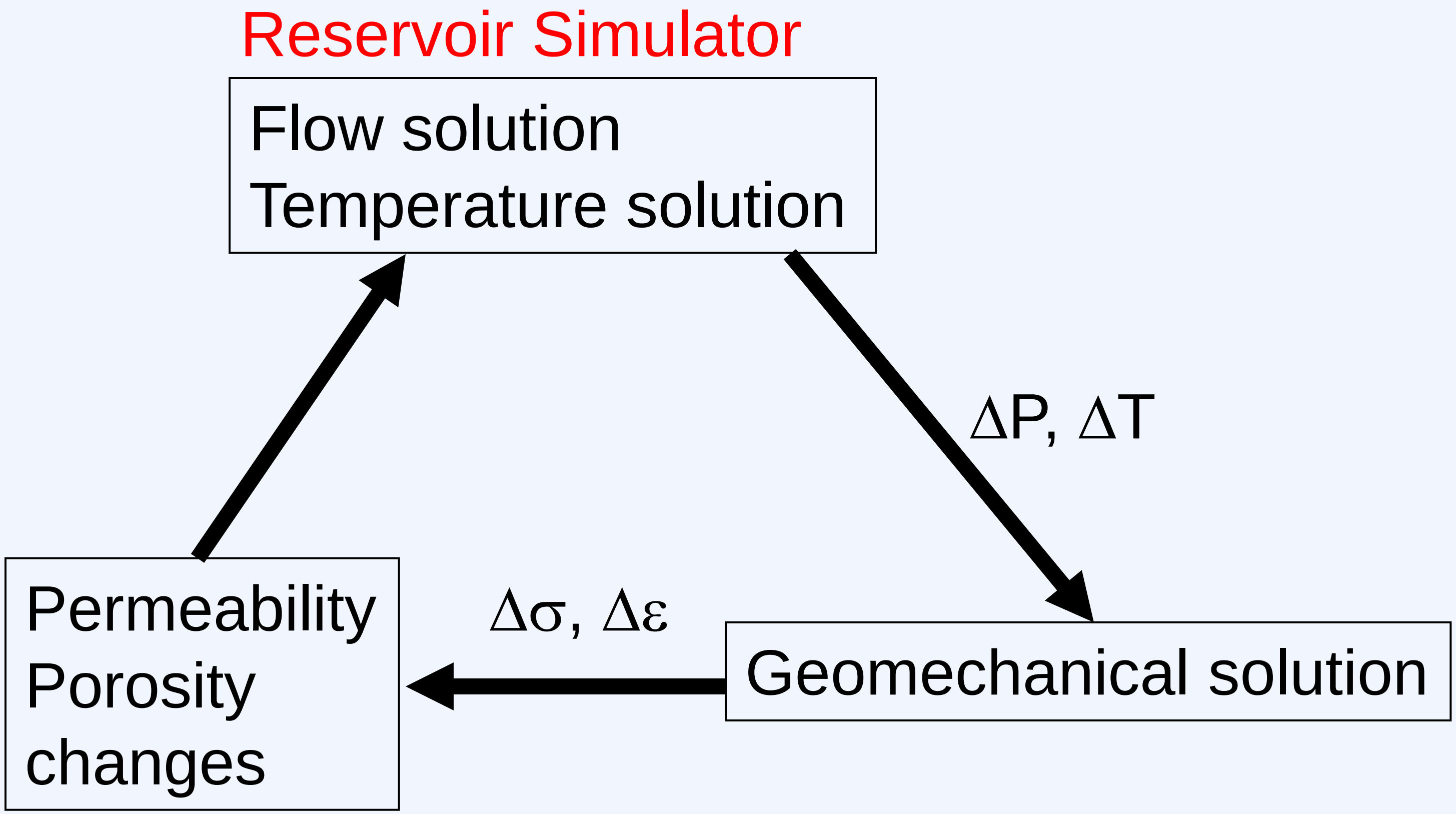




47 field cases
("unfractured")

Numerical
modelling

Coupling geomechanics-flow



Natural shear fractures or faults vs: induced shearing of natural fractures or faults

Natural

Department of Geology University of Texas at Arlington

Induced shearing

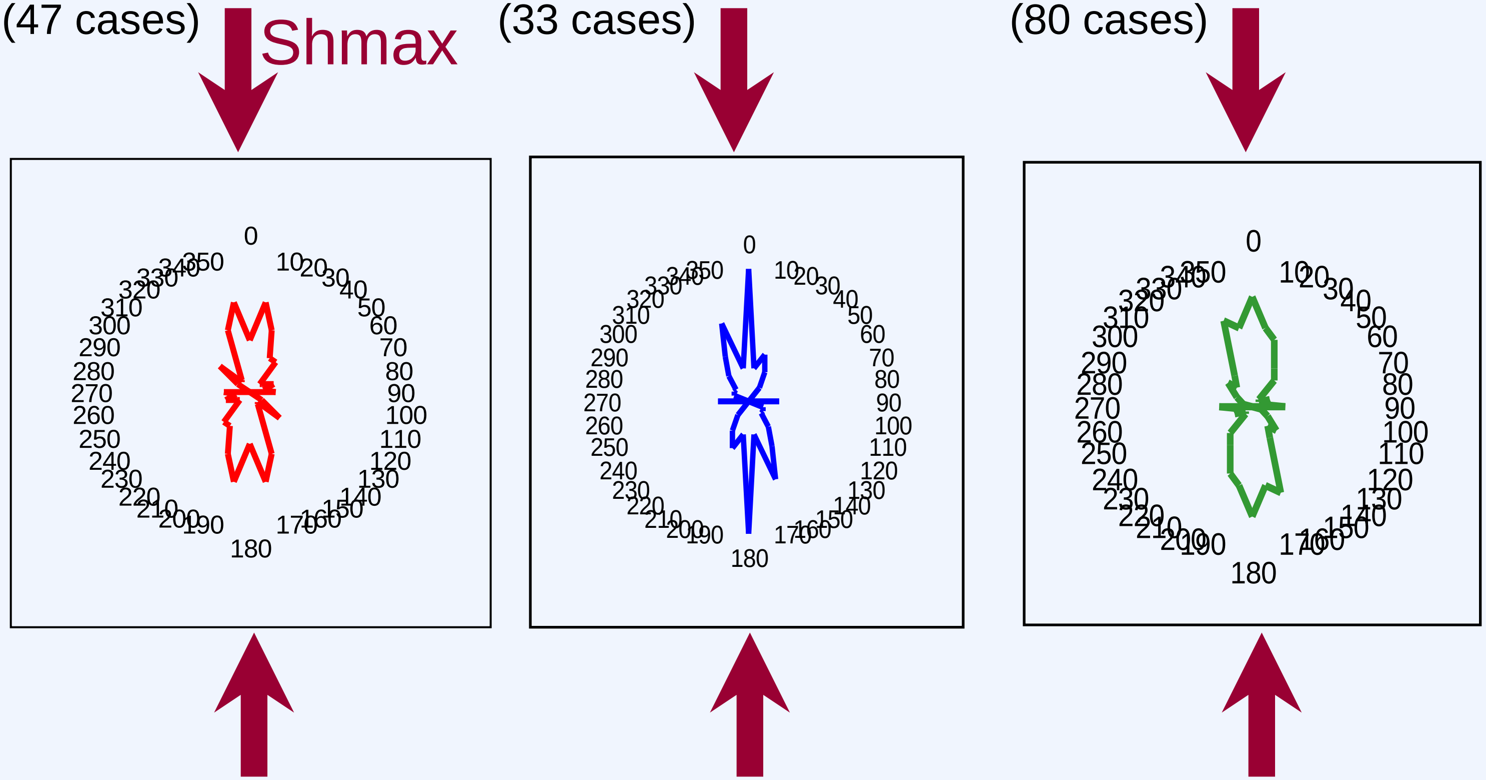
-on *either* an extensional fracture or a fault
-possibly opposite sense of shear from natural
-generally small displacements

Flood Directionality & Stress State
Field evidence

‘Unfractured’ Reservoirs (47 cases)

‘Fractured’ Reservoirs (33 cases)

All Reservoirs (80 cases)



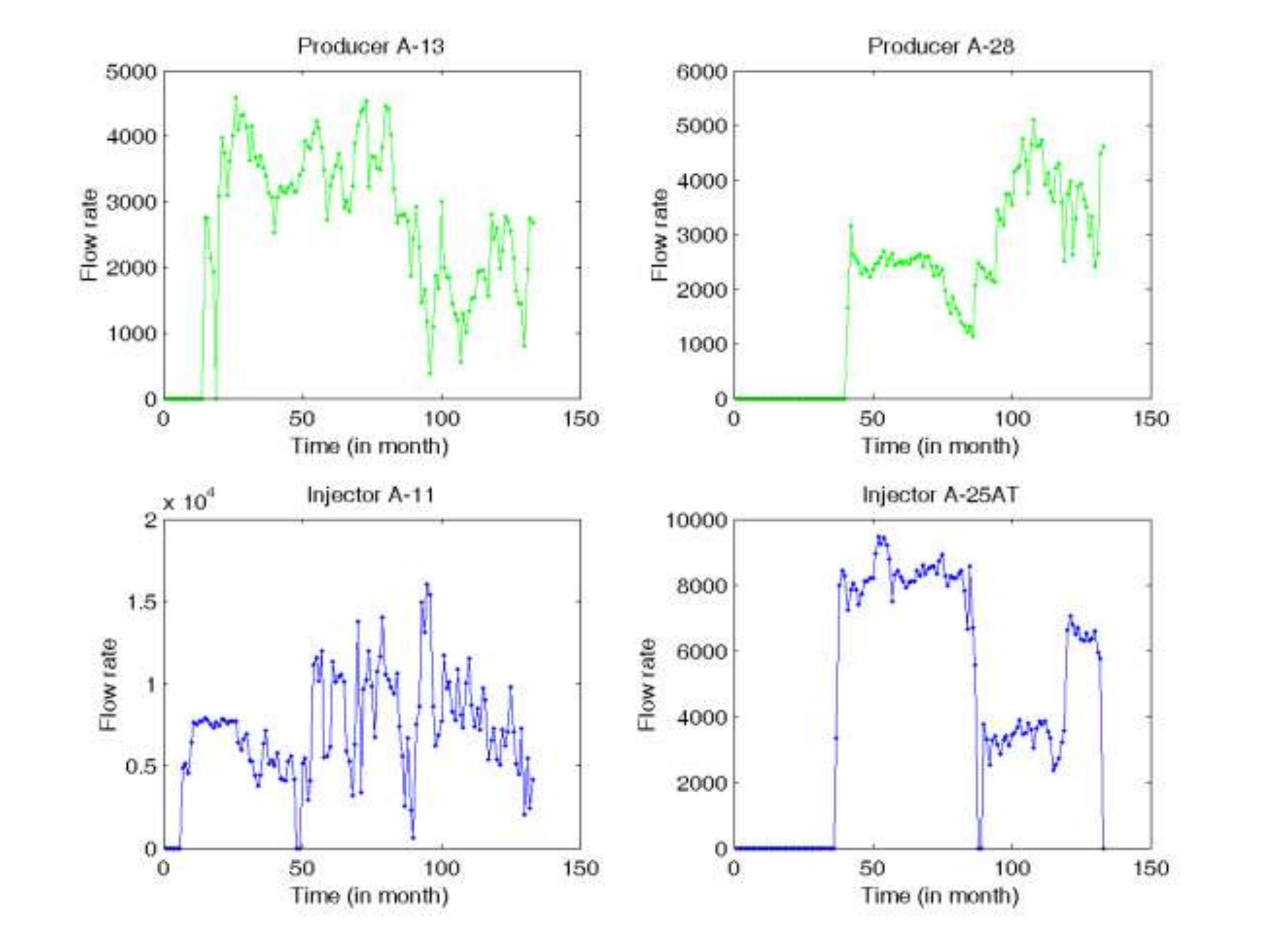
Practical exploitation

- Anisotropy is not homogeneous but related to heterogeneities (faults & fractures)
- Method for early diagnosis of reservoir breakthrough paths:
- *Correlations in well-rate fluctuations*

Flow rate fluctuations

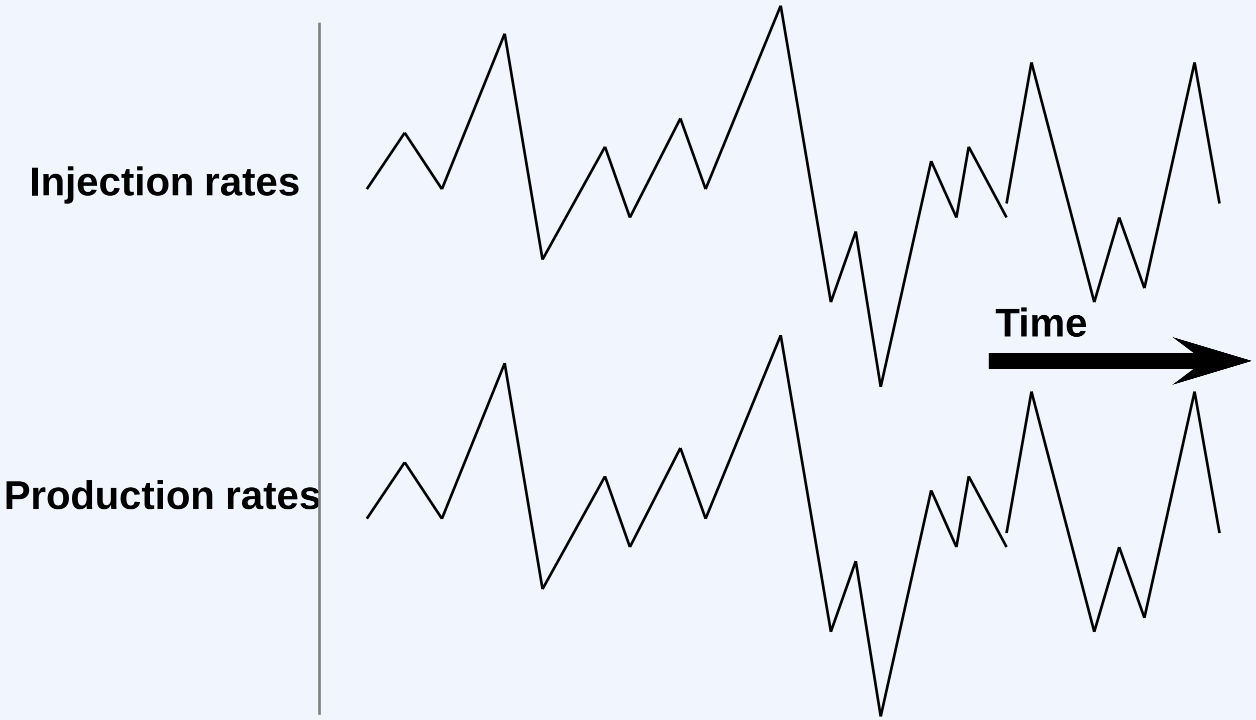
Producers

Injectors



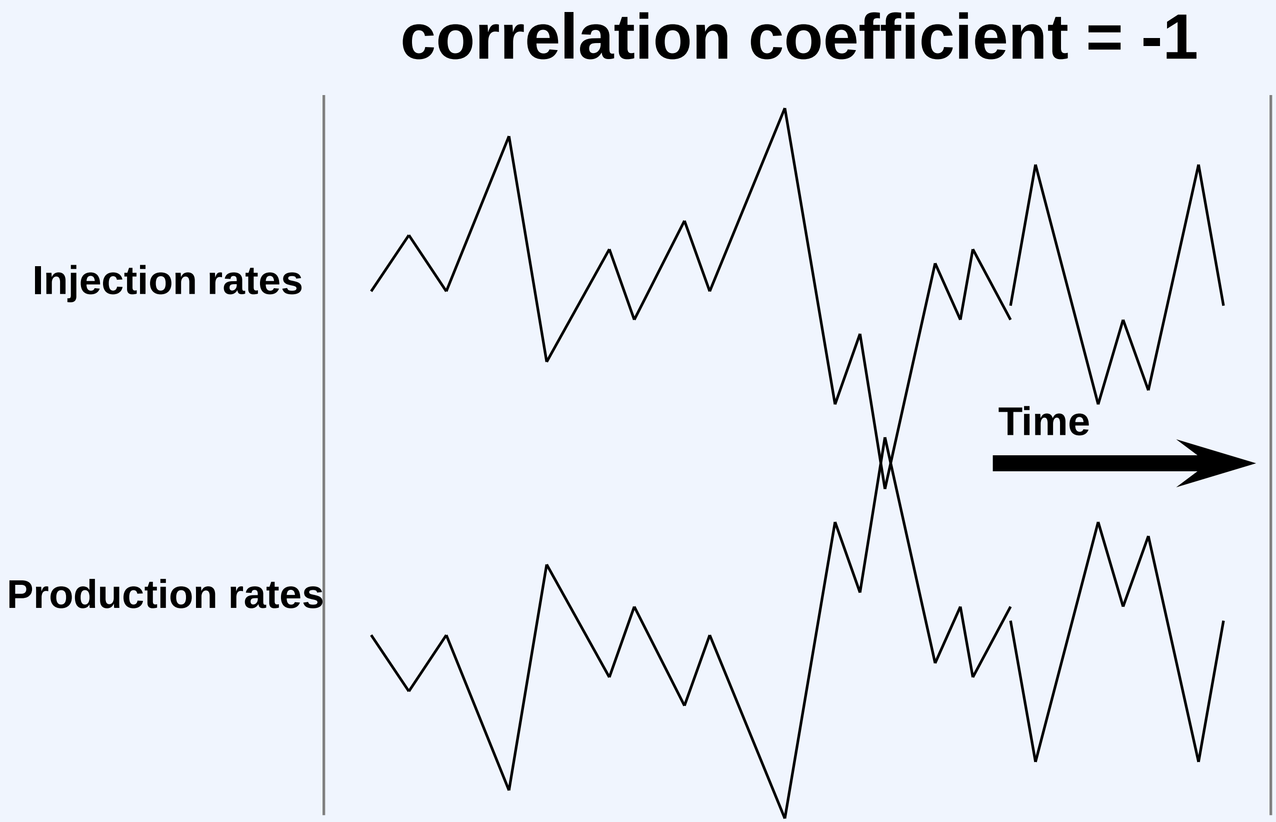
Rate correlation analysis

correlation coefficient = +1



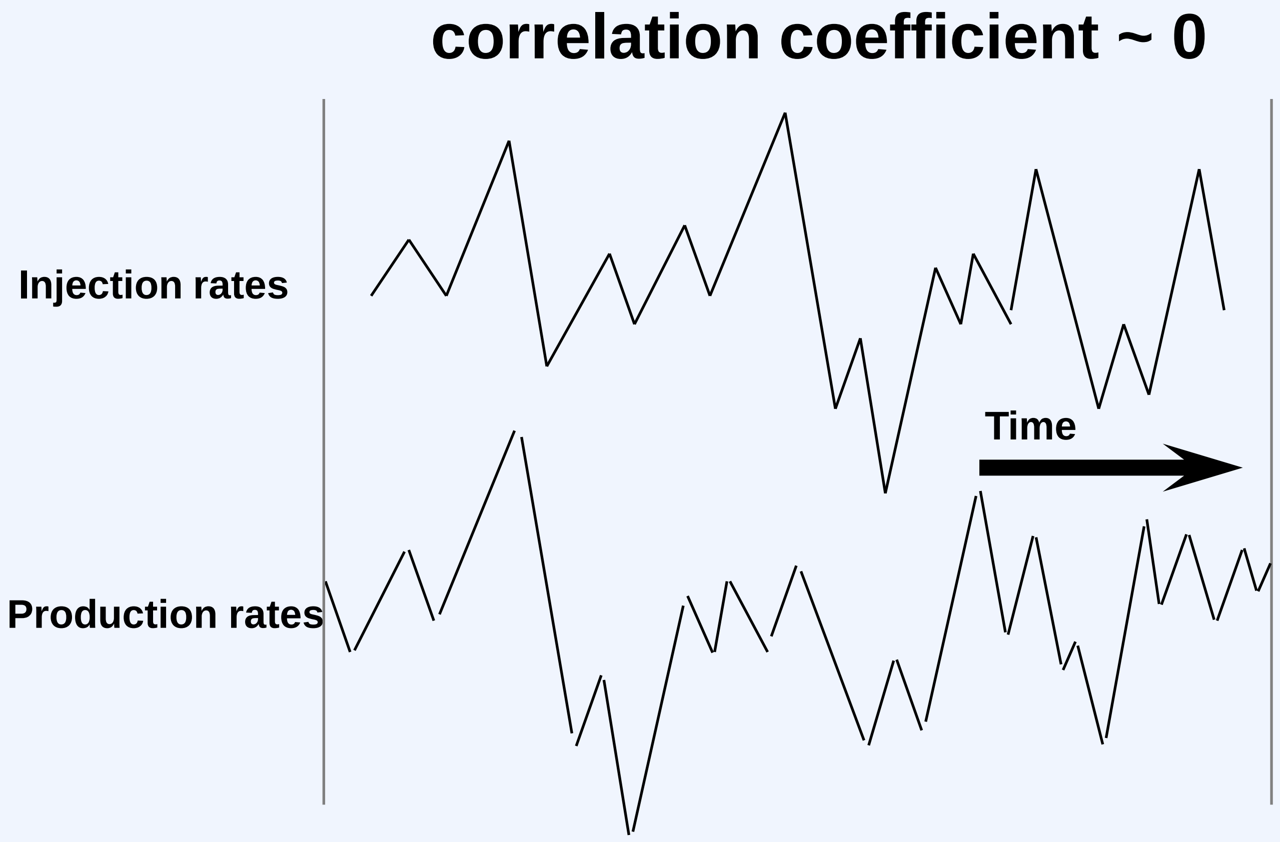
+1 represents perfectly correlated data sets

Rate correlation analysis



-1 represents perfectly anti-correlated data sets

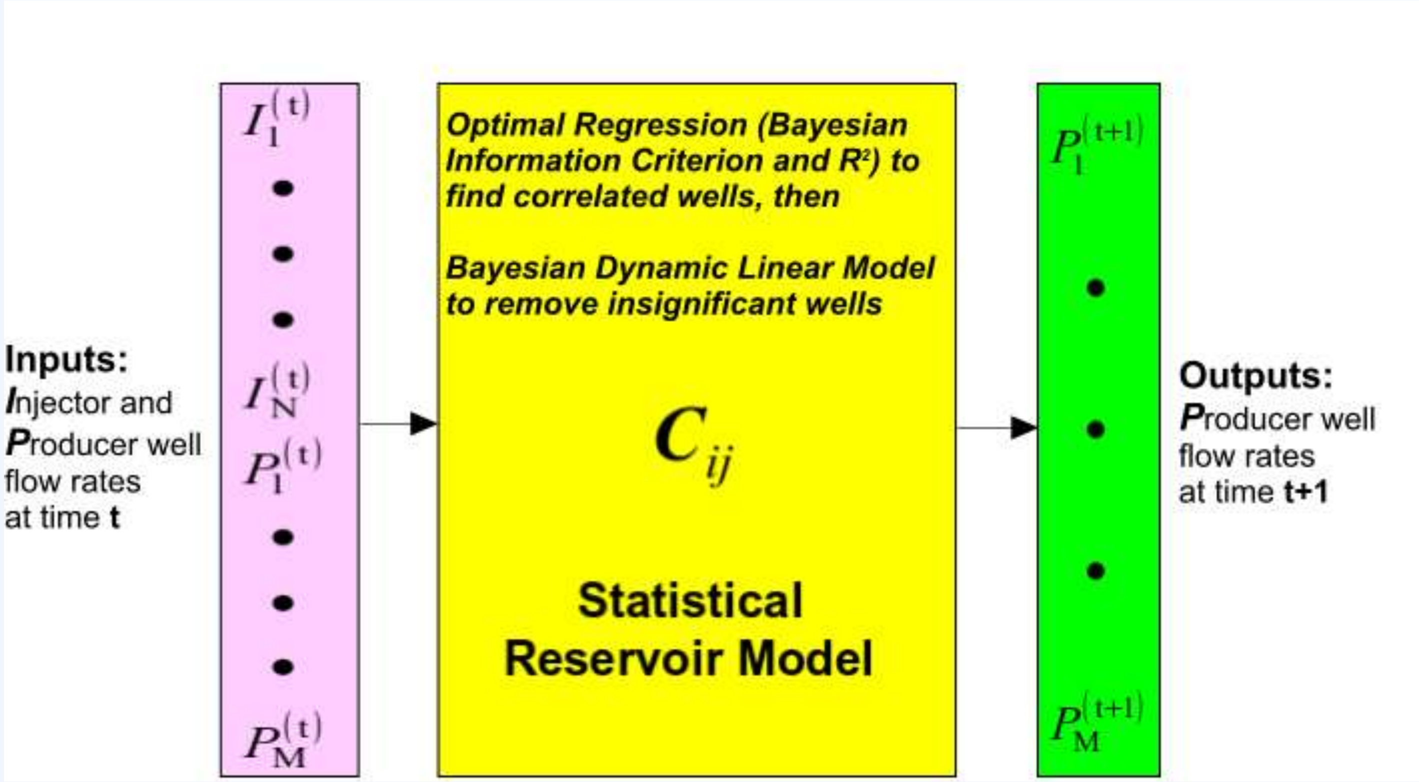
Rate correlation analysis



Measures of correlation

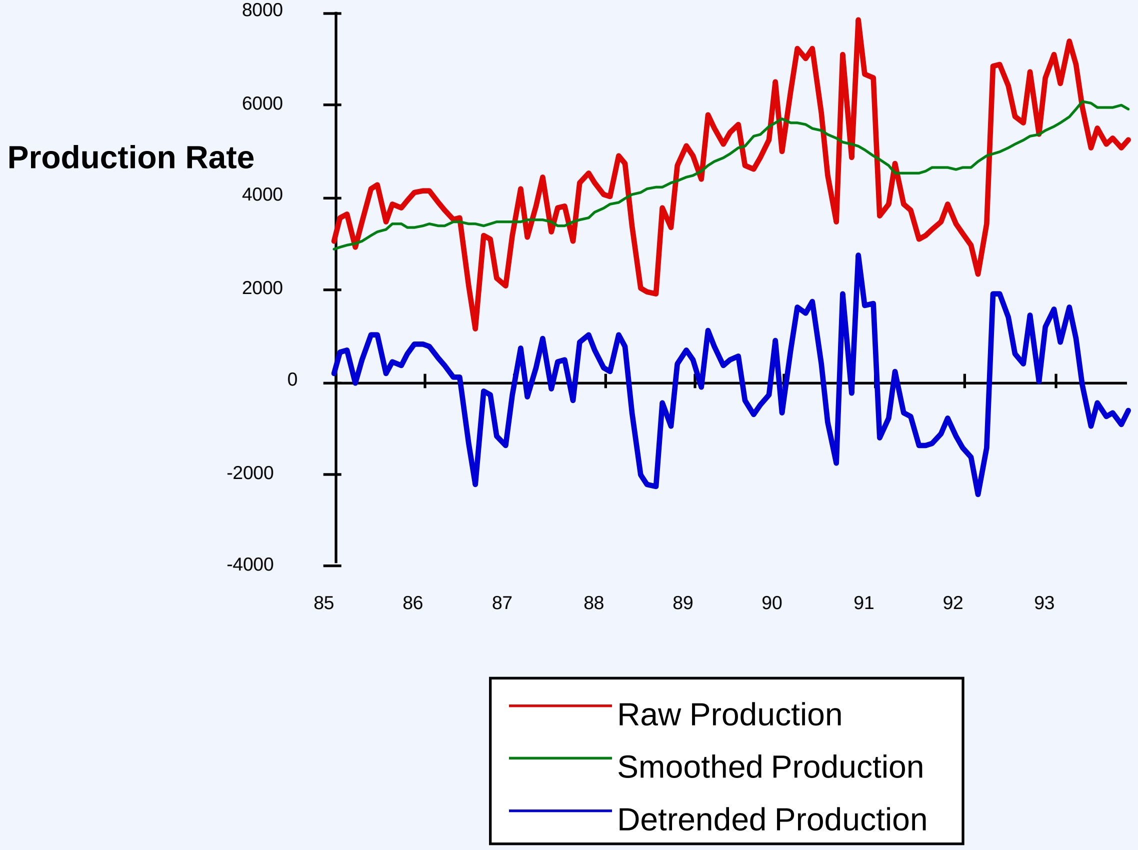
- Pearson correlation
- Spearman rank correlation
- Kendall’s tau correlation
- Multilinear regression
- Statistical Reservoir Model

Statistical Reservoir Model

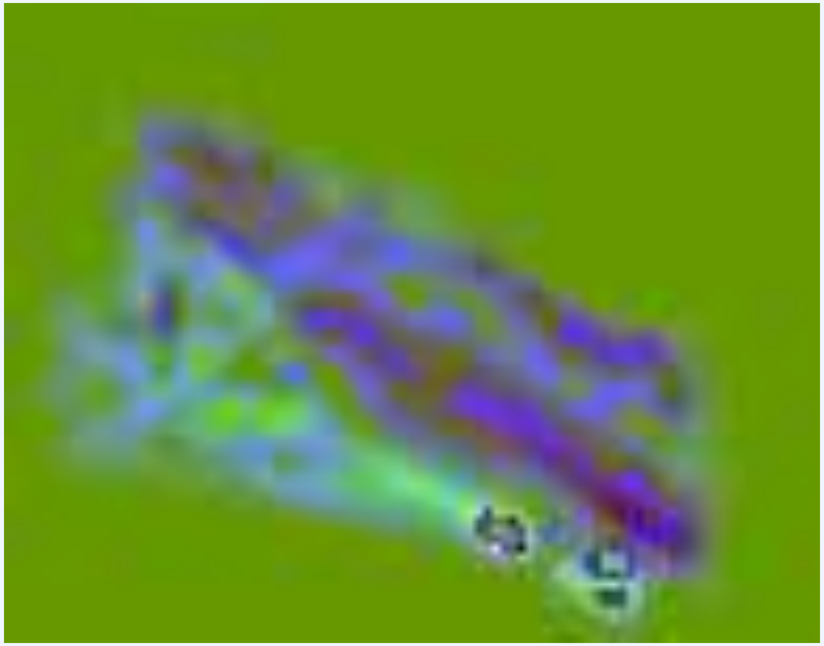


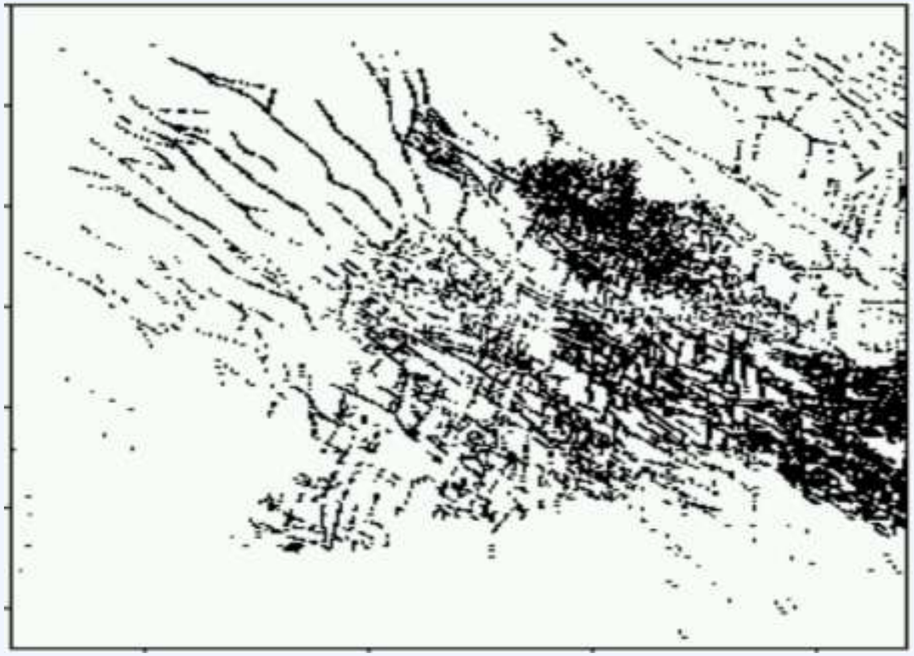
- Finds best small group of wells to model flow rate of any well of interest

Rate Correlations -
Raw and Detrended (hi-pass filtered) data



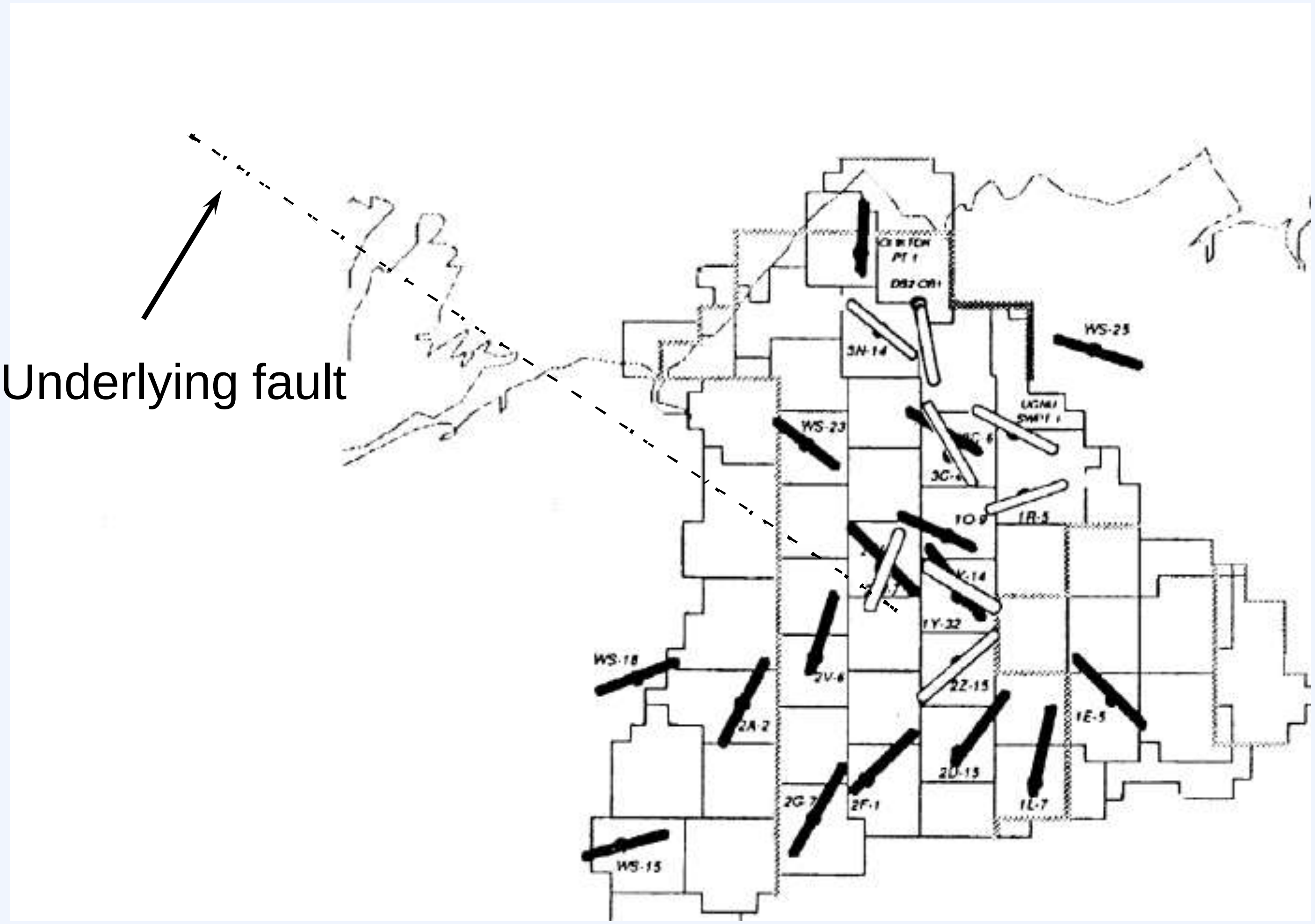
Field A - rate correlation coefficients interpolated between well pairs





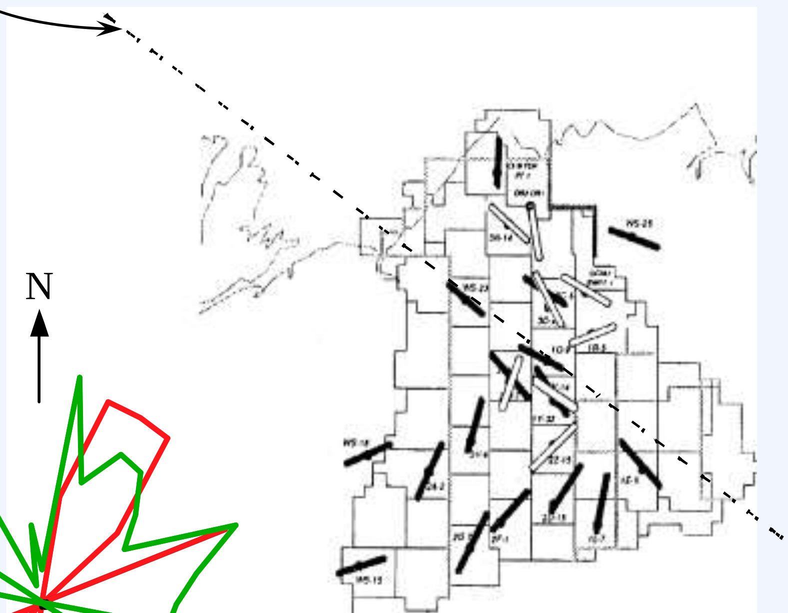
This map is a simple interpolation of rate correlations between individual well pairs. Nevertheless it shows characteristics of the fault pattern in the reservoir, even showing breaks in trends at the points of fault relay ramps.

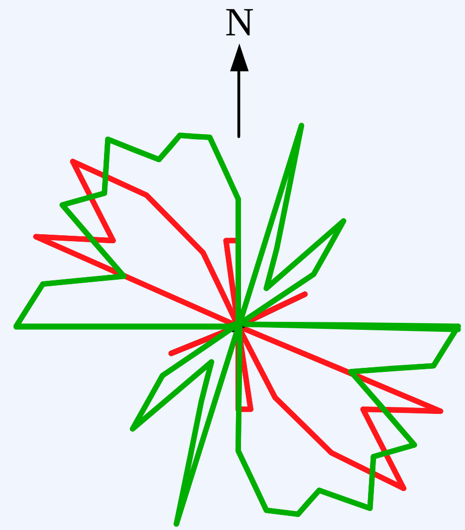
Field B.
Field measurements of Shmax



Field B. Rate Correlation Results

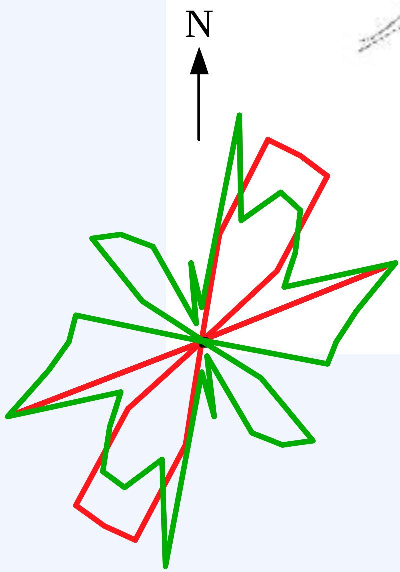
Basement Fault trend





Northeast Region

Shmax from borehole breakout



Principal Horizontal Stress Direction (Shmax)

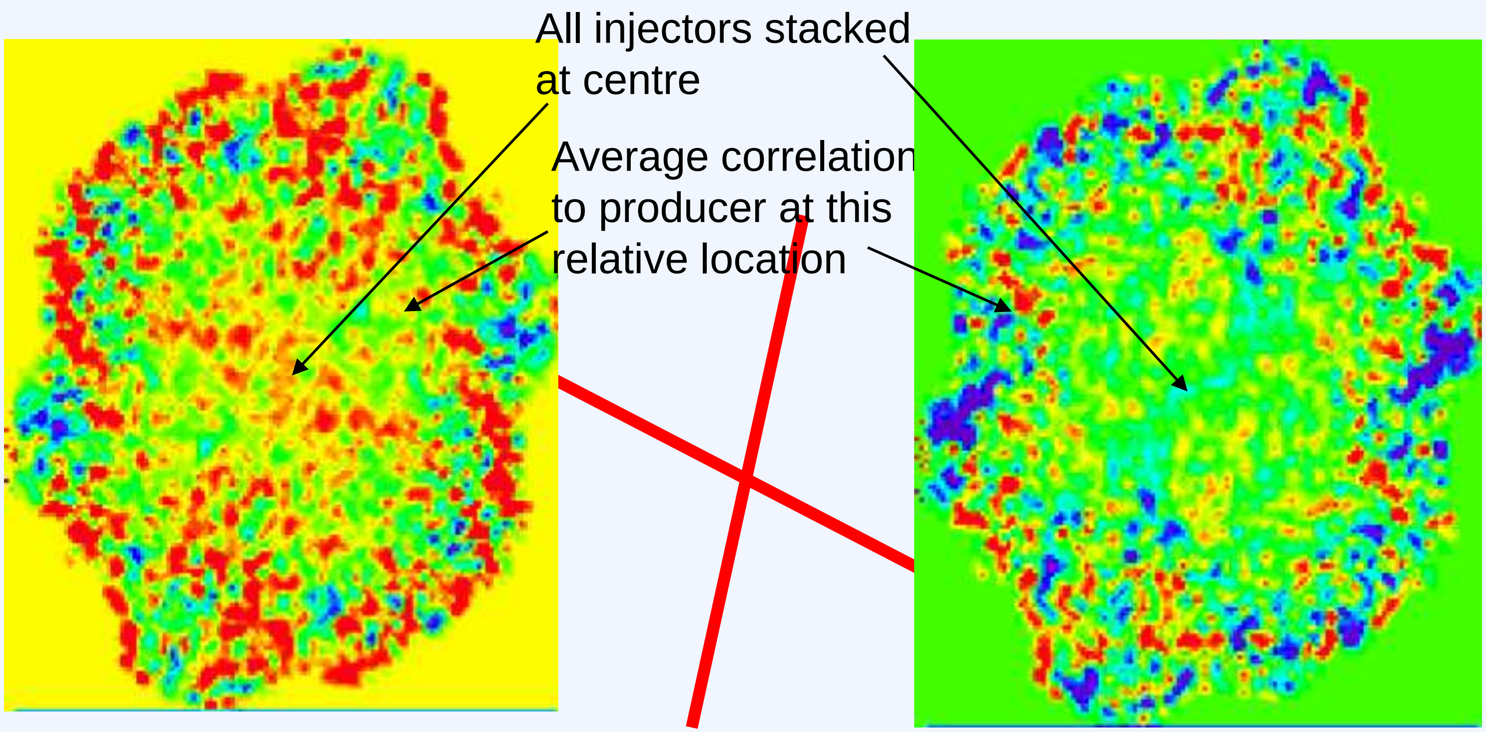
Spearman Rank Correlation Analysis Results

Southwest Region

⇛ Rate correlations are related to stress state

Spatial arrangement

(Spatial autocorrelation of time correlation in flowrates)
Field B



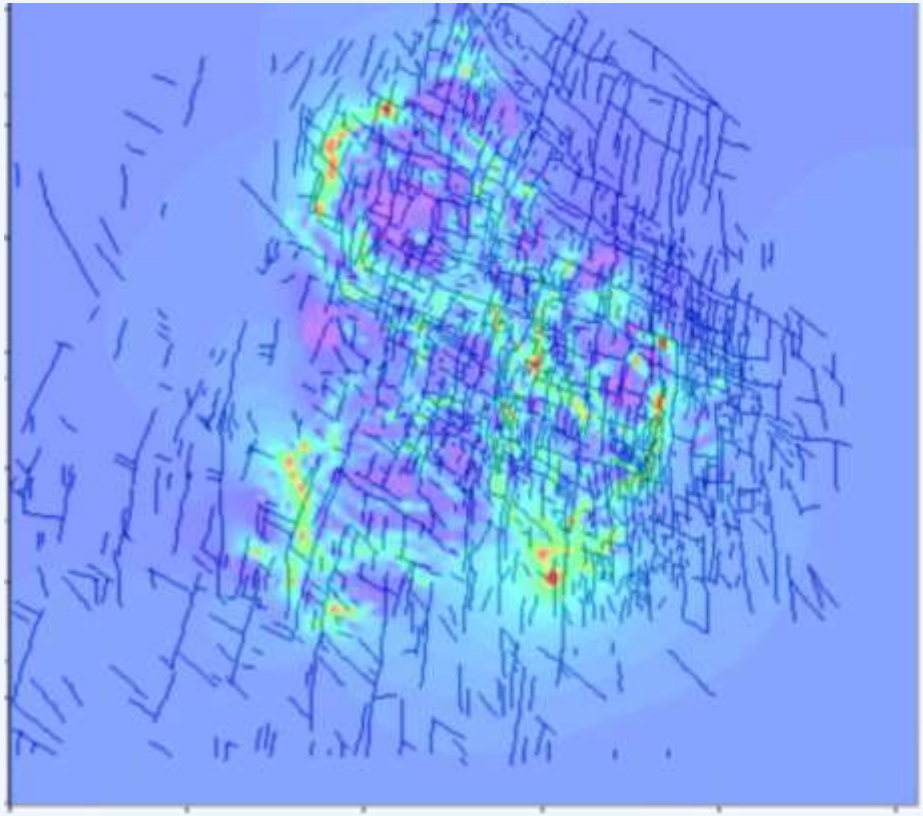
From raw rate data | Fault trends | From detrended rate data

⇛ Rate correlations are spatially long-range

Field B. First principal component (spatially interpolated) of matrix of rate correlations

(represents 18.6% of all variance in rate fluctuations)

Overlay fault traces

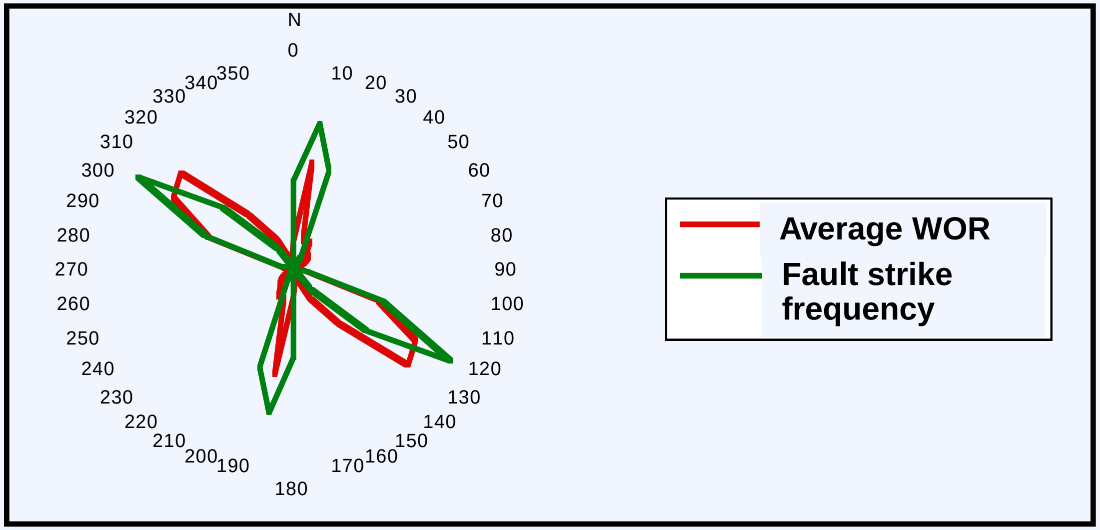


⇛ Rate correlations are related to faults

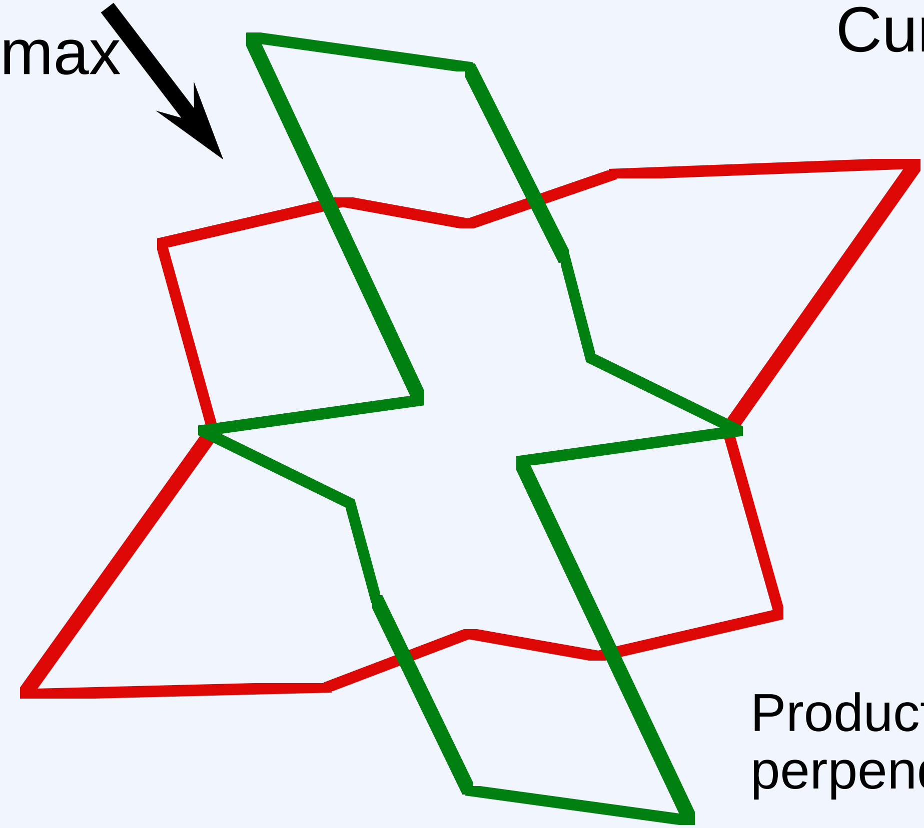
Field B. Stress and water production

Interpolated stress trajectory map

Water production as a function of the local orientation of Shmax



The Prize – field B data



Cumulative production per well

1.0 WOR

1.0 MMBO

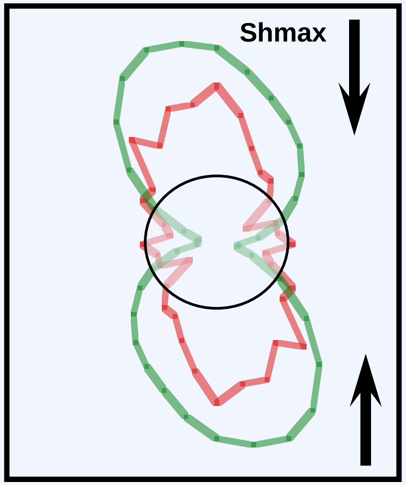
Production is greatest perpendicular to stress

WOR greatest parallel to stress

Directionality in rate correlations

(aggregated data)

Directionality relative to stress state

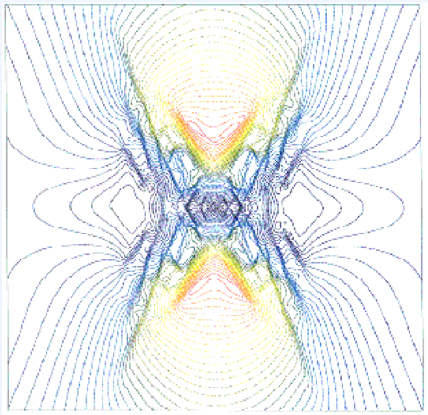


Rate correlations between well pairs
– over 0.5 million in 8 field areas

Raw rate fluctuations
Detrended fluctuations
— zero correlation

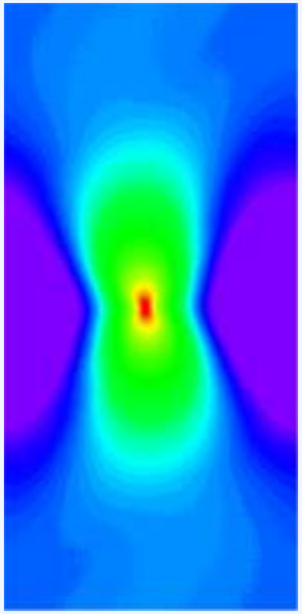
Coupled modelling supports directionality

modelled response to progressive cooling from central injector with permeability update according to normal strains on fractures



total displacements

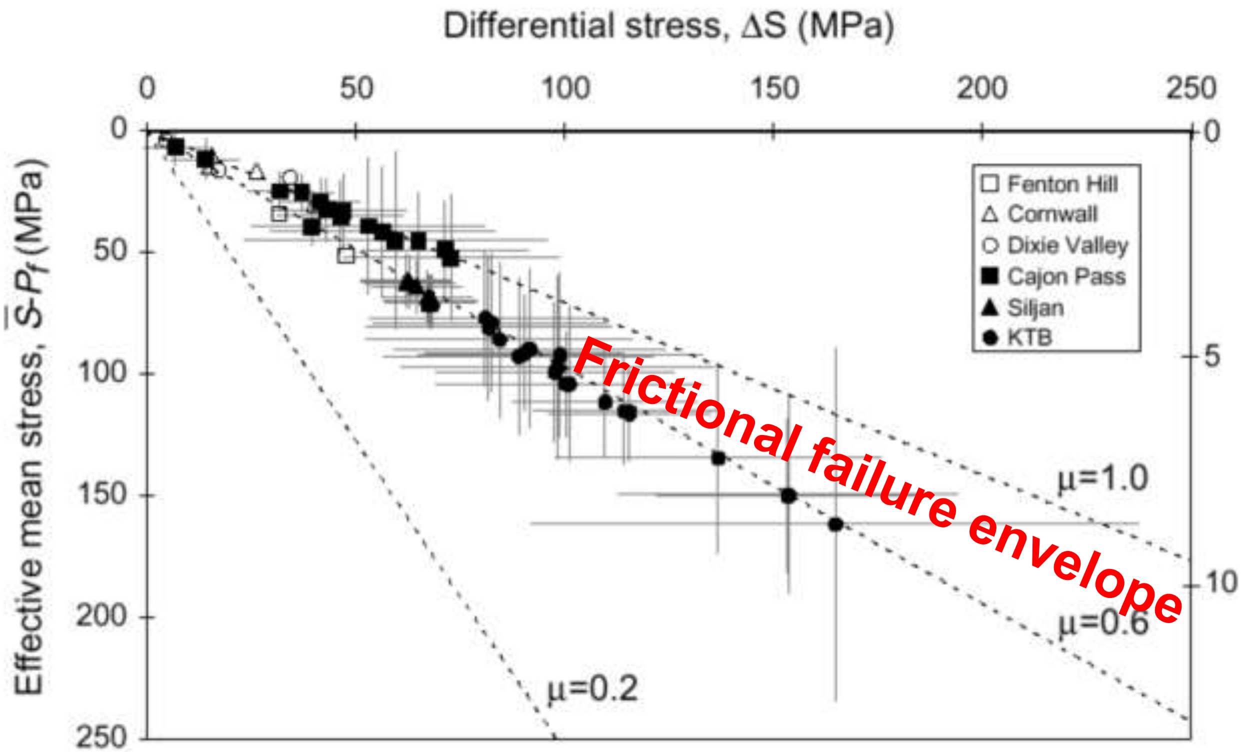
Areal distribution of correlation in xx-strain ~ 1/r



⇒ Rate correlations are reflecting strain changes related to stress

Evidence for critically stressed crust
Directly measured stress states

From: Townend & Zoback



Geology: May 2000; v. 28; no. 5; p. 399–402; 4 figures; 1 table.

Conceptual mechanism

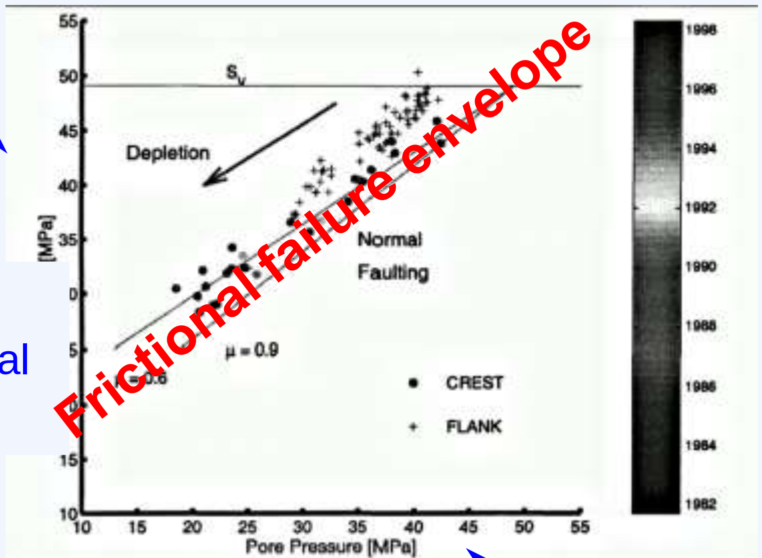
- Near critical stress states
- Permeability changes with stress

Stress state tracking frictional failure envelope during depletion

Zoback & Zinke Pure appl. geophys. 159 (2002) 403-420

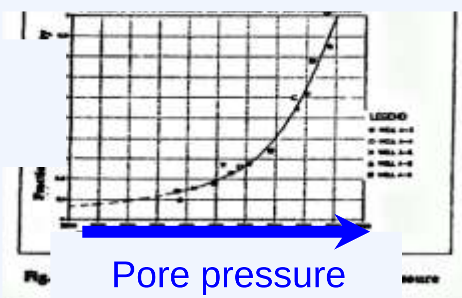
Valhall

Least principal stress



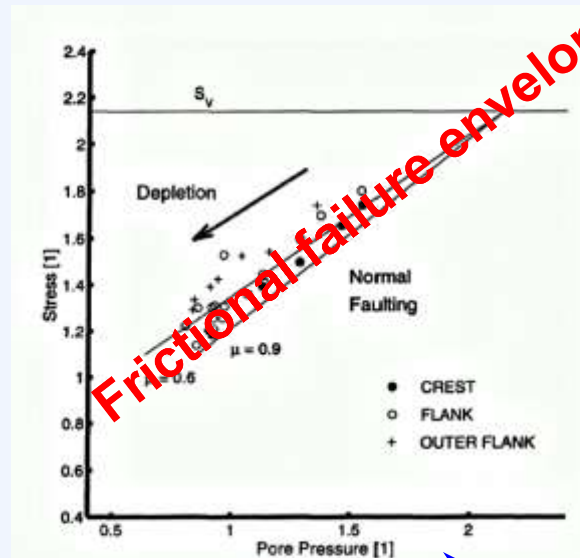
Fracture permeability declined with reservoir pressure in the early life of Valhall (SPE 24914)

Well test permeability



Pore pressure

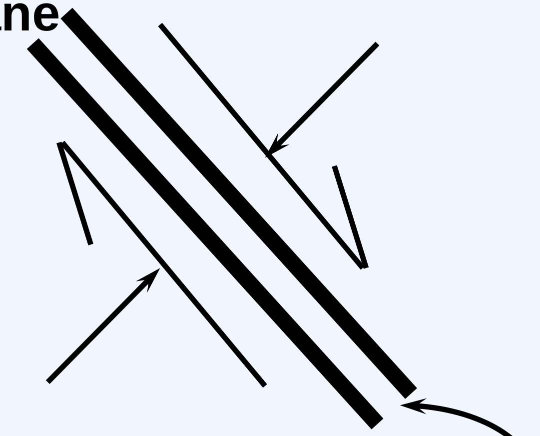
Ekofisk

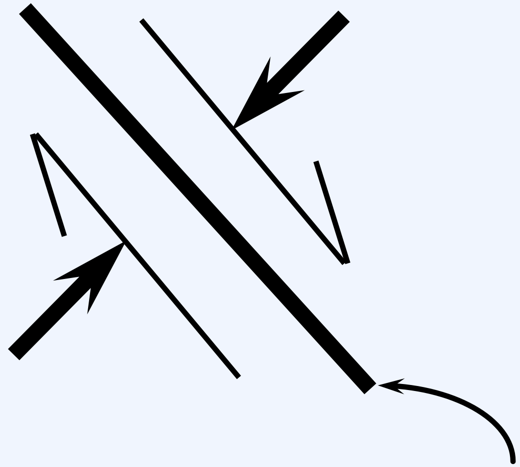


Pore pressure

Permeability maintained through reservoir depletion

Fracture conductivity can go up or down when activated in shear





Fault conductivity INCREASES when SHEARING occurs under LOW NORMAL stress	Fault conductivity REDUCES when SHEARING occurs under HIGH NORMAL stress

Critically stressed fractures

Zoback & Townend (2001)

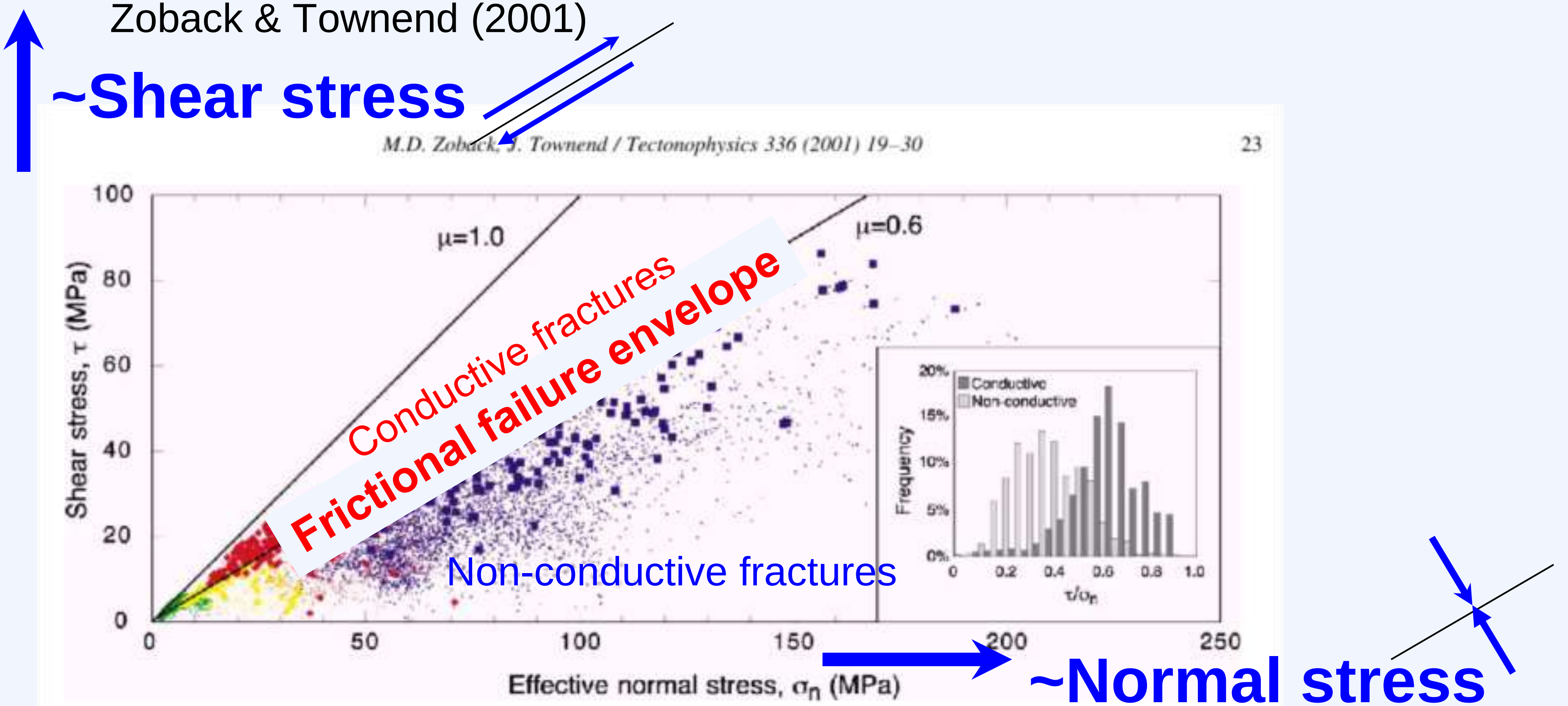
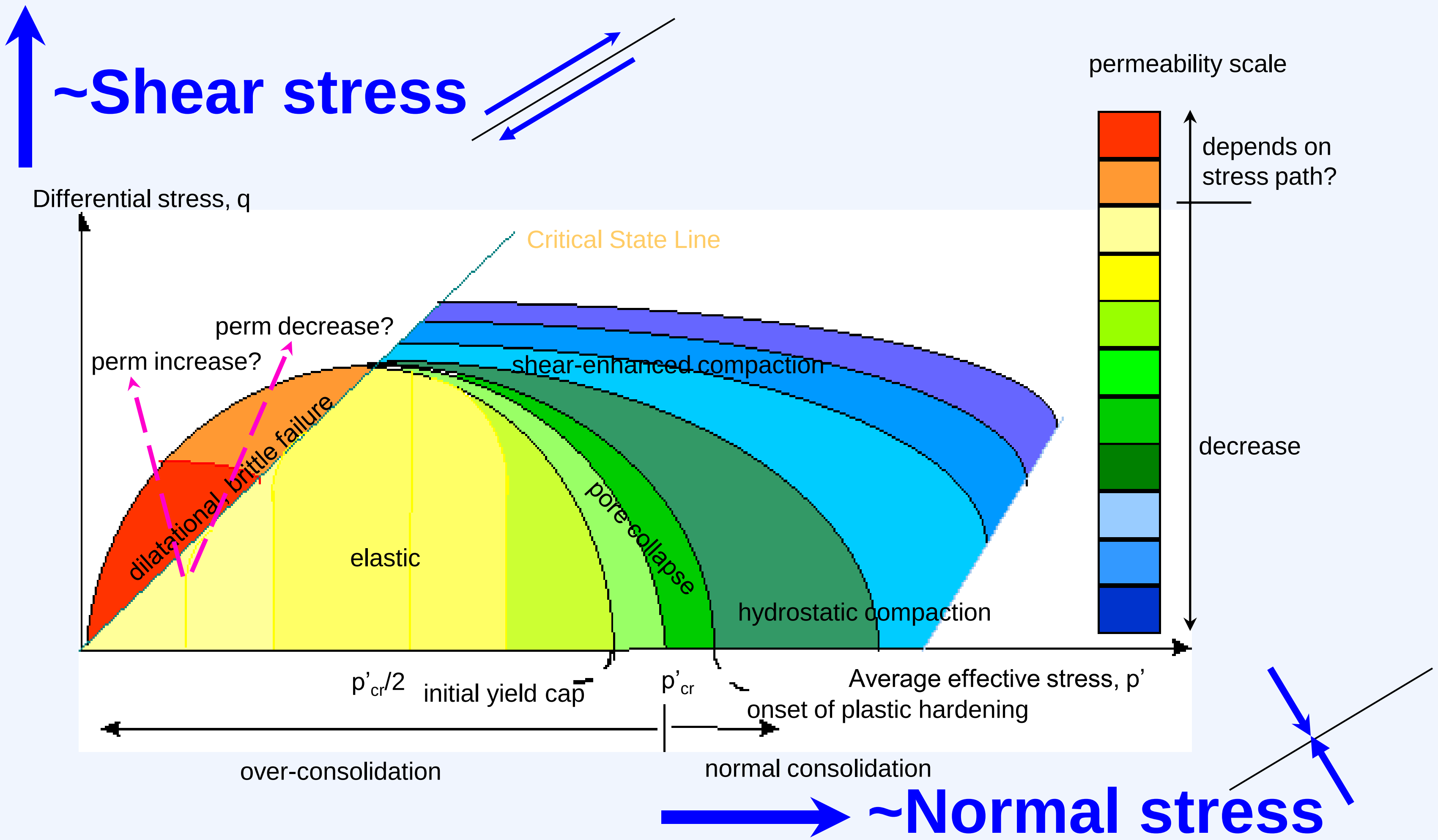


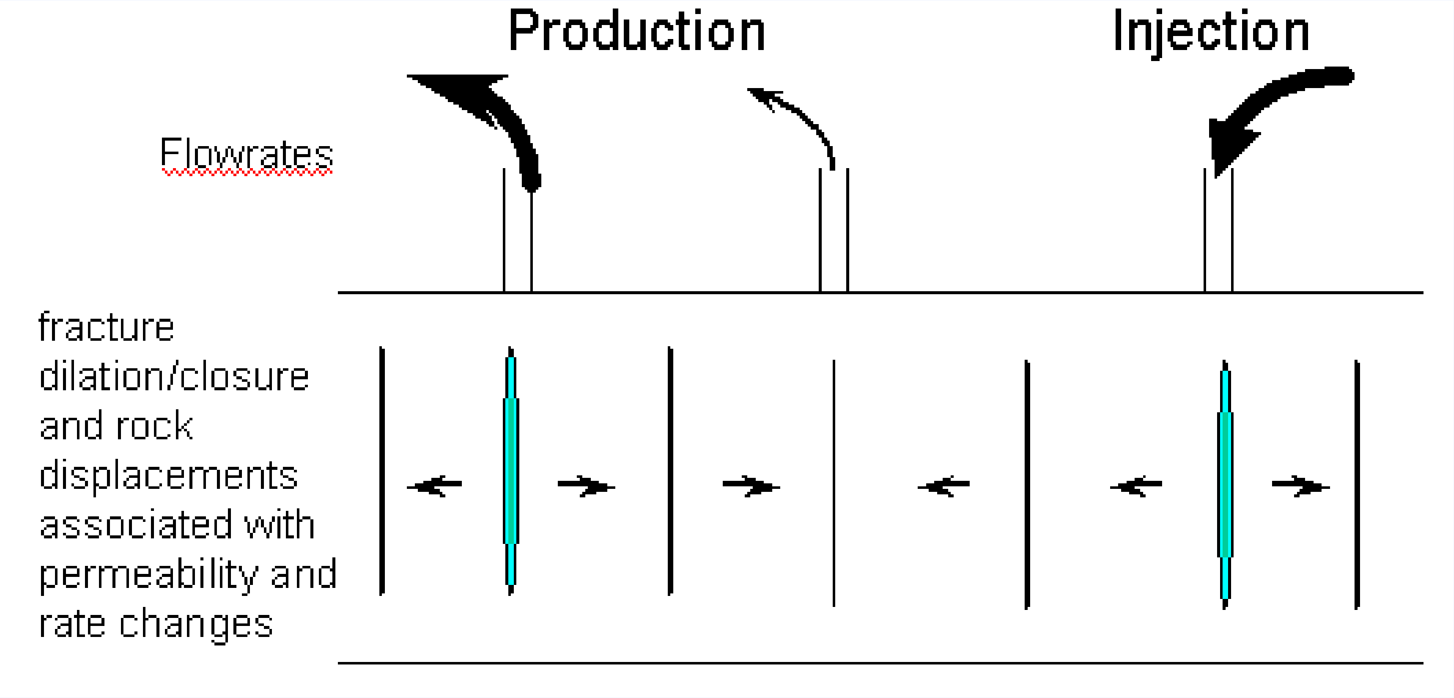
Fig. 2. Shear and effective normal stresses on fractures identified using borehole imaging techniques in the Cajon Pass (red diamonds and dots), Long Valley (yellow triangles and dots), Nevada Test Site (green circles and dots), and KTB (blue squares and dots) boreholes. The larger, filled symbols represent hydraulically conductive fractures and faults, and the dots represent non-conductive fractures. The inset figure illustrates the range in shear to normal stress ratio for all four datasets combined. The number of data in each dataset is normalized so that each dataset has equal weight. Original data from Barton et al. (1995) and Ito and Zoback (2000).

Permeability-stress map for weak reservoirs

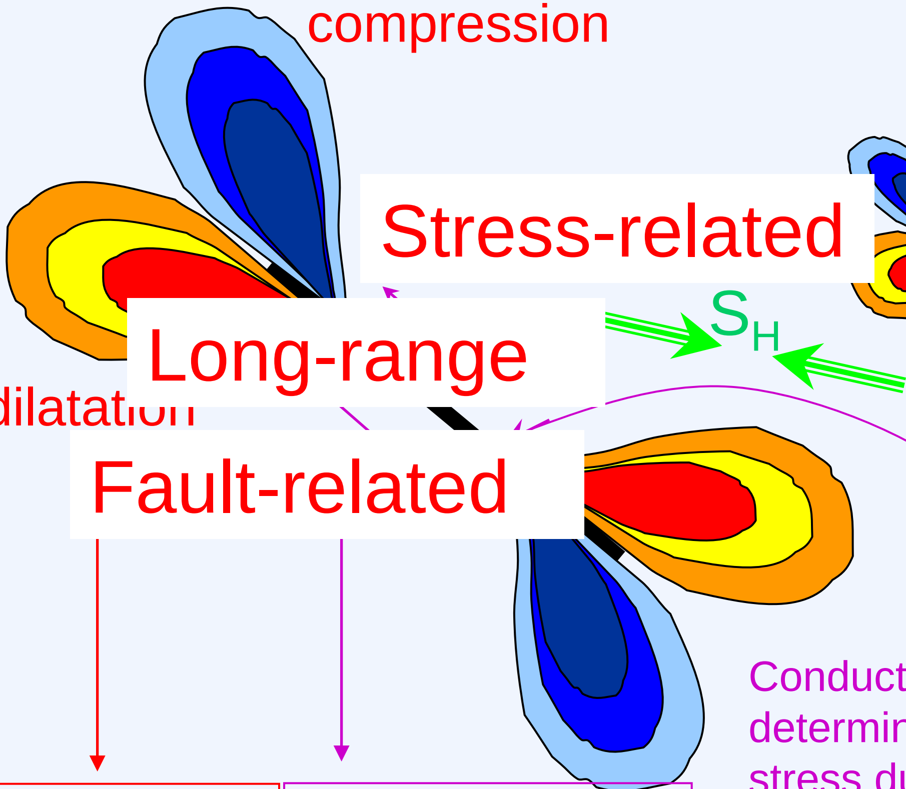


conceptual after Zhu & Wong (1997) and Crawford et al (1999)

Basic concept



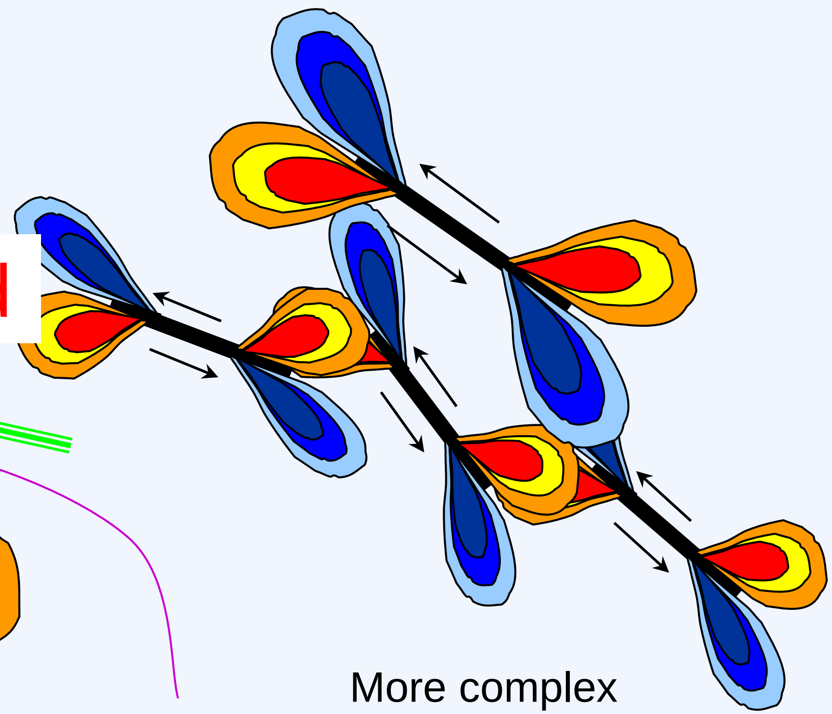
Concept of long-range transmission of strain by shear



local cause | *transmission*

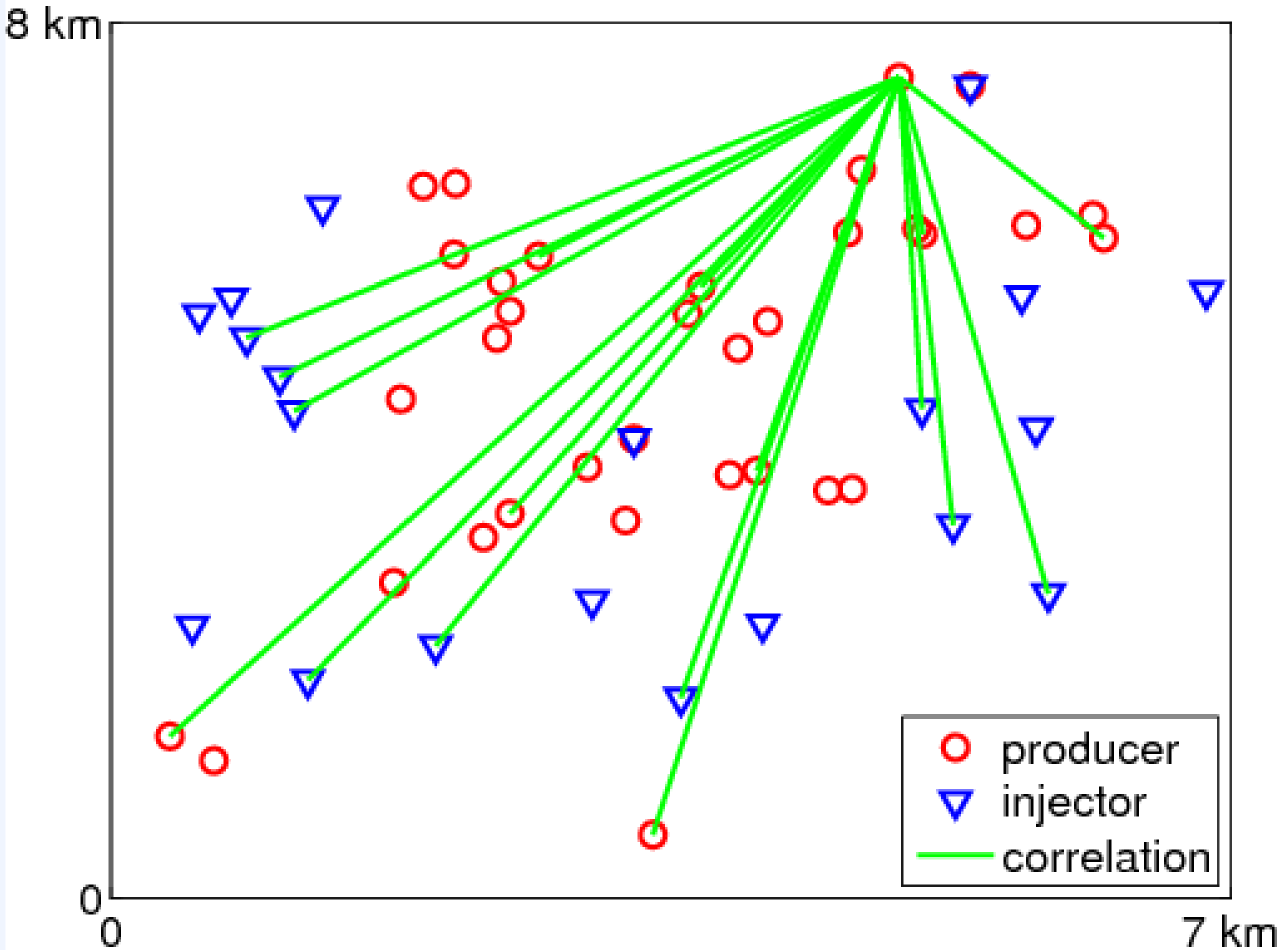
of rate changes

Conductivity determined by normal stress during shear vs rock strength, ductility, damage zone, displacement etc

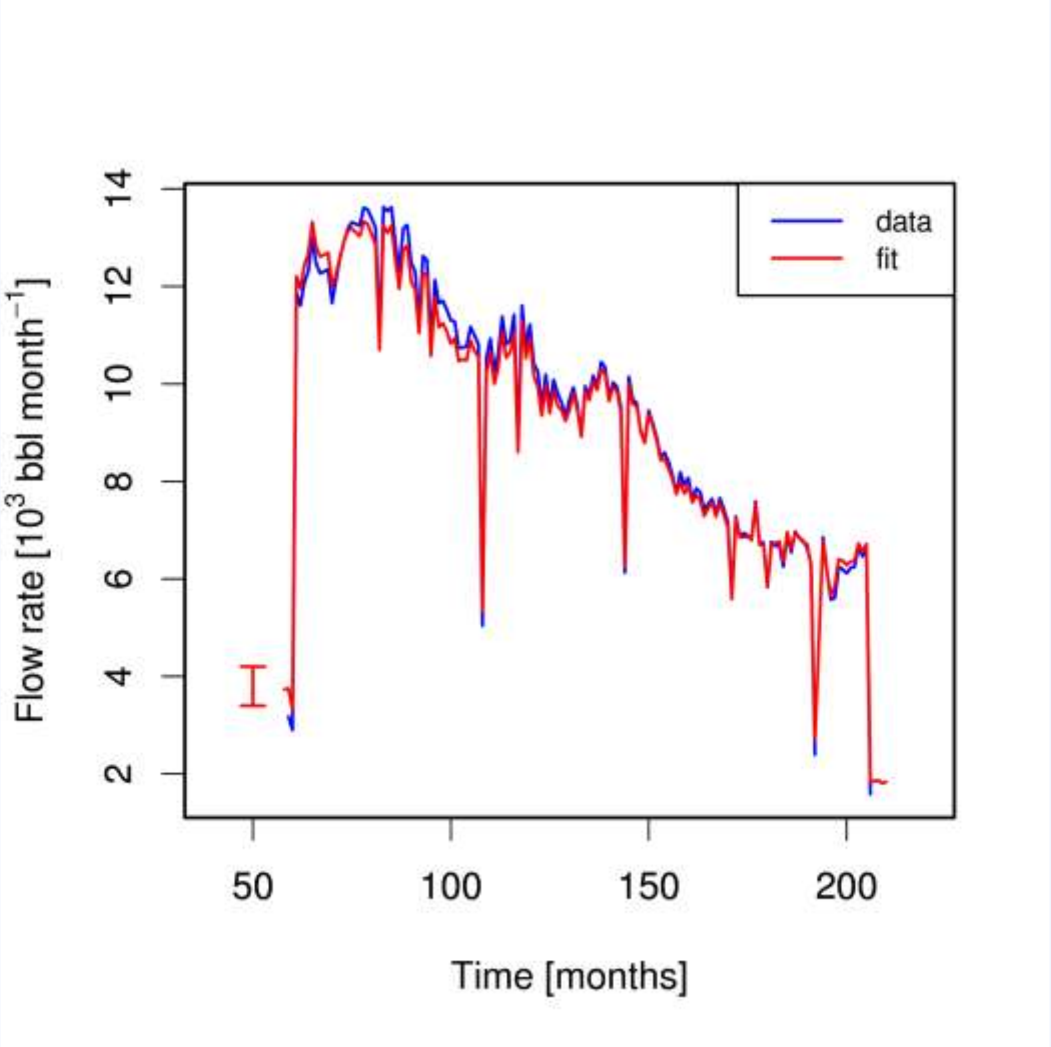


More complex discontinuous shear

Statistical Reservoir Model
Example of correlated wells

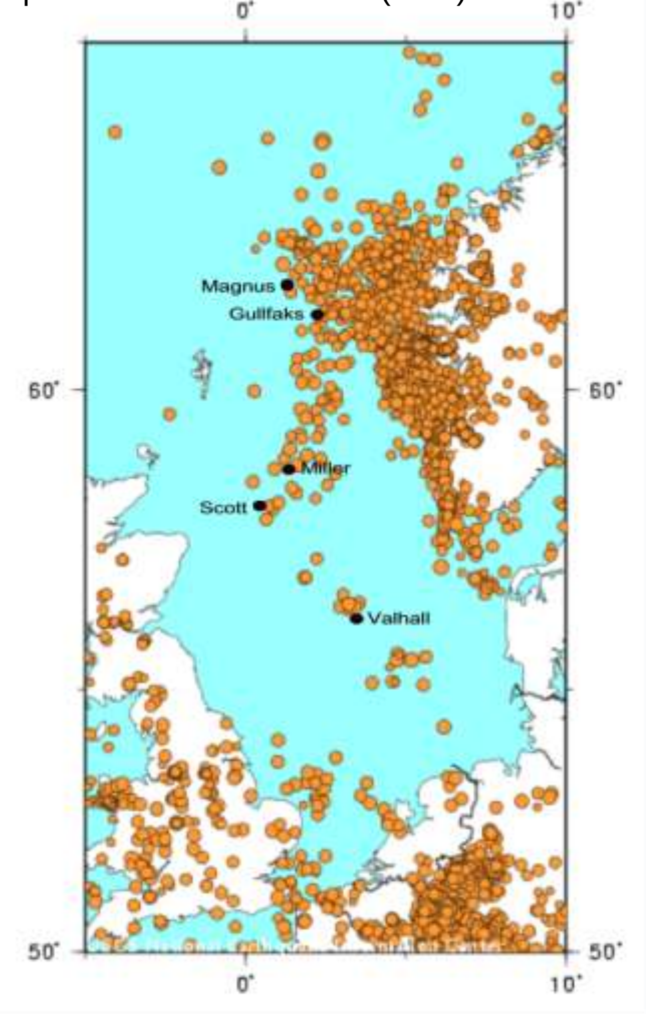


Statistical Reservoir Model History Match Well 15 (R^2=1.0, σ=3%)

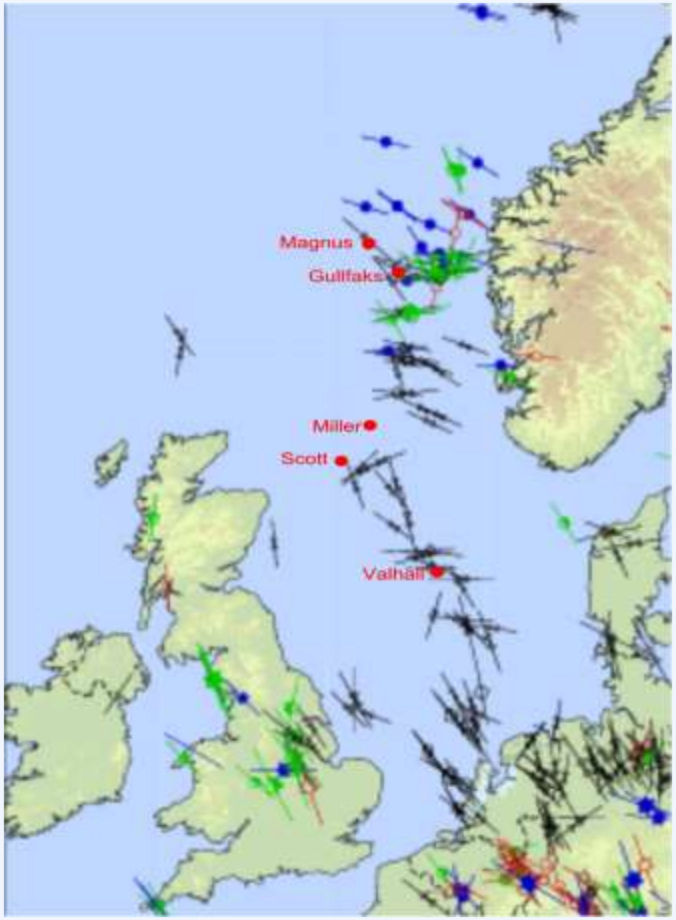


Neotectonic setting of North Sea

Earthquake epicentres (US Geological Survey/National Earthquake Information Center (PDE) 1973 - Present)



Maximum horizontal stress axes
(World Stress Map Heidbach et al (2008))

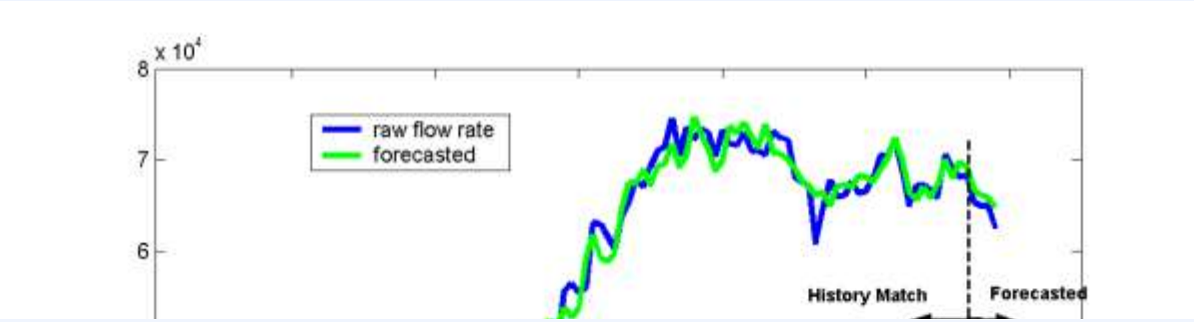


Statistics of fits & forecasts

	Field 1	Field 2	Field 3	Field 4	Field 5
Producers output (out of those with 10+ months data)	73/118	34/36	37/48	70/81	16/17
Mean predictors per producer (out of total predictors with 10+ months data)	12/159 (8%)	13/59 (22%)	8/72 (11%)	9/82 (11%)	4/26 (15%)
Mean R^2 over all producers	0.92	0.90	0.96	0.95	0.97
Mean error σ over all producers [%]	17	33	17	24	22
Error σ on total production [%]	7	11	16	14	21

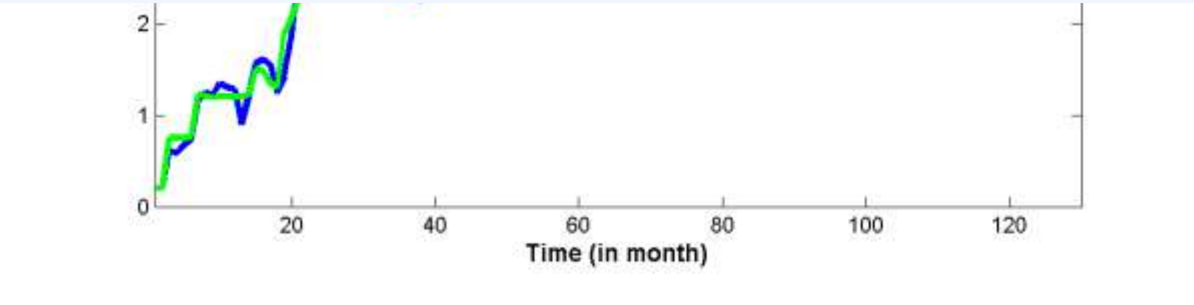
Total production errors ~2 x size if only use previous month as fit

Short-term rate prediction

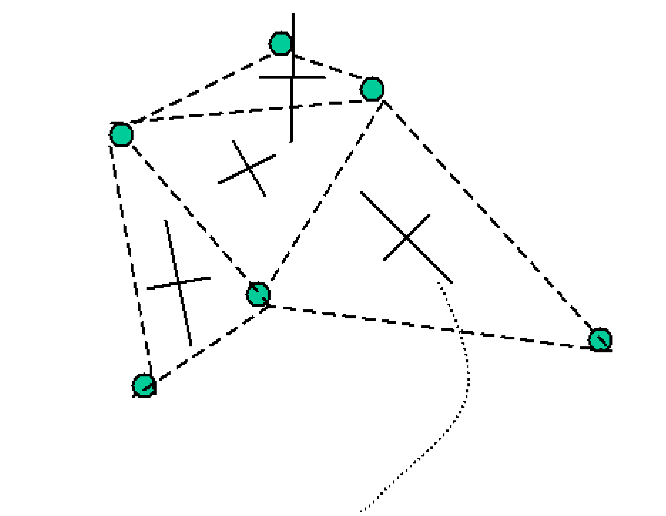


Blind test of prediction with SRM of 3 months of Gullfaks production (refereed by Rock Deformation Research, University of Leeds)

"The actual production figures for most (>70%) of the wellbores lie within the 95% confidence limits given by Edinburgh."



Extraction of *rate diffusivities* from time-behaviour of rate correlations



Diffusivity tensor constant across each element

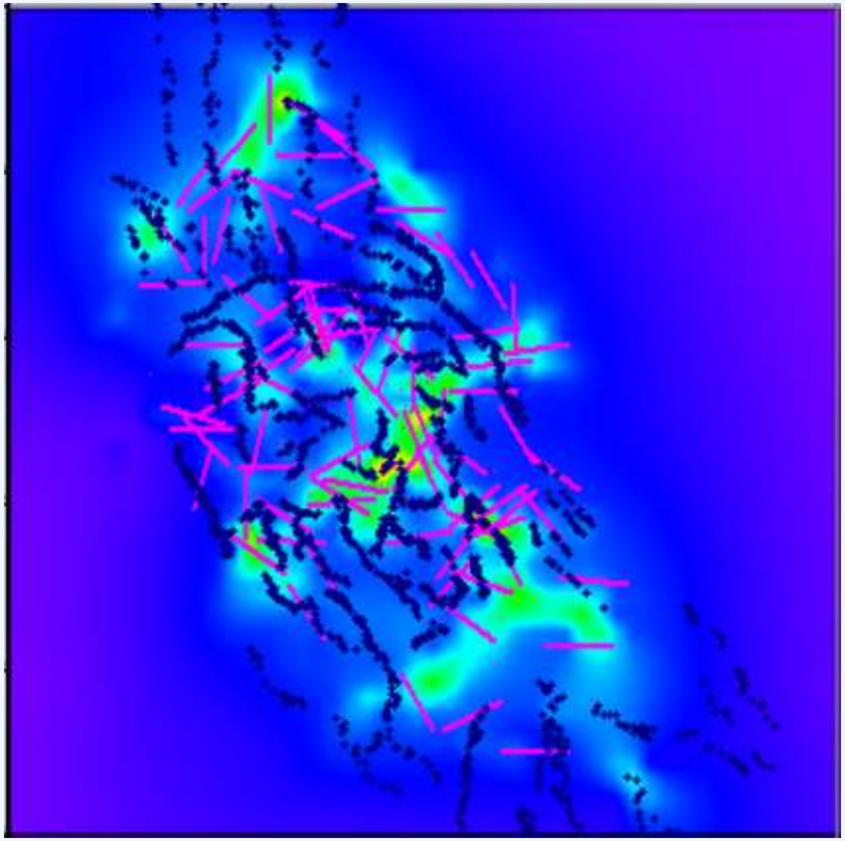
Looking to extract tensors related to *diffusive* rate behaviour:

- –Local (shorter-range)
- –Non-oscillatory in time
- –Fitted with non-negative diffusivities
- – (Decaying in time)

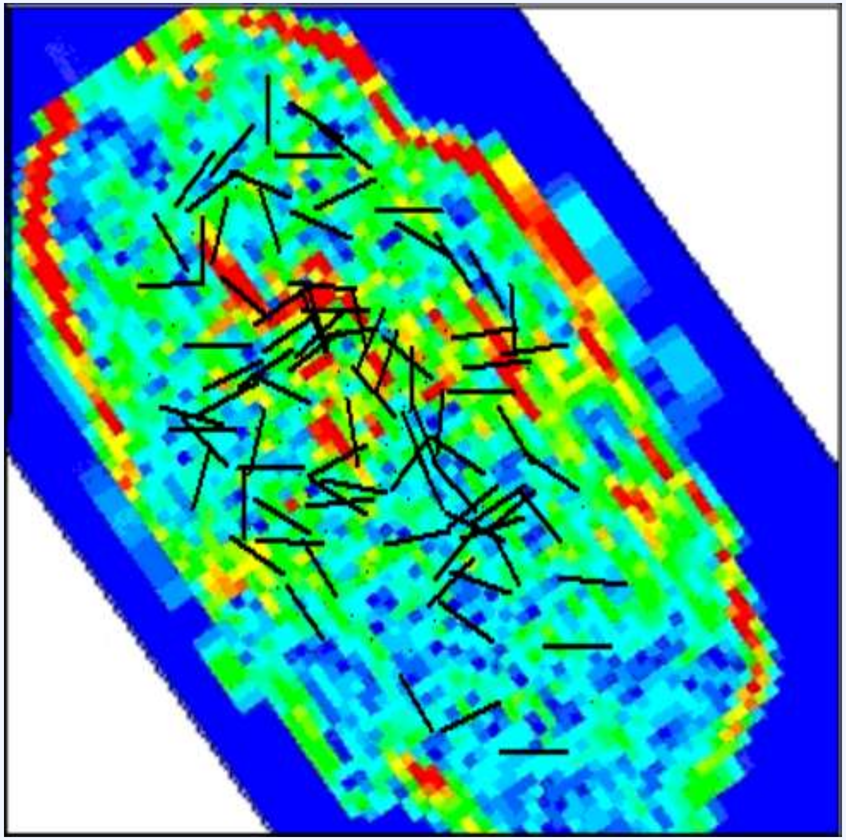
Likely to be related to *permeability tensors.*

Valhall field

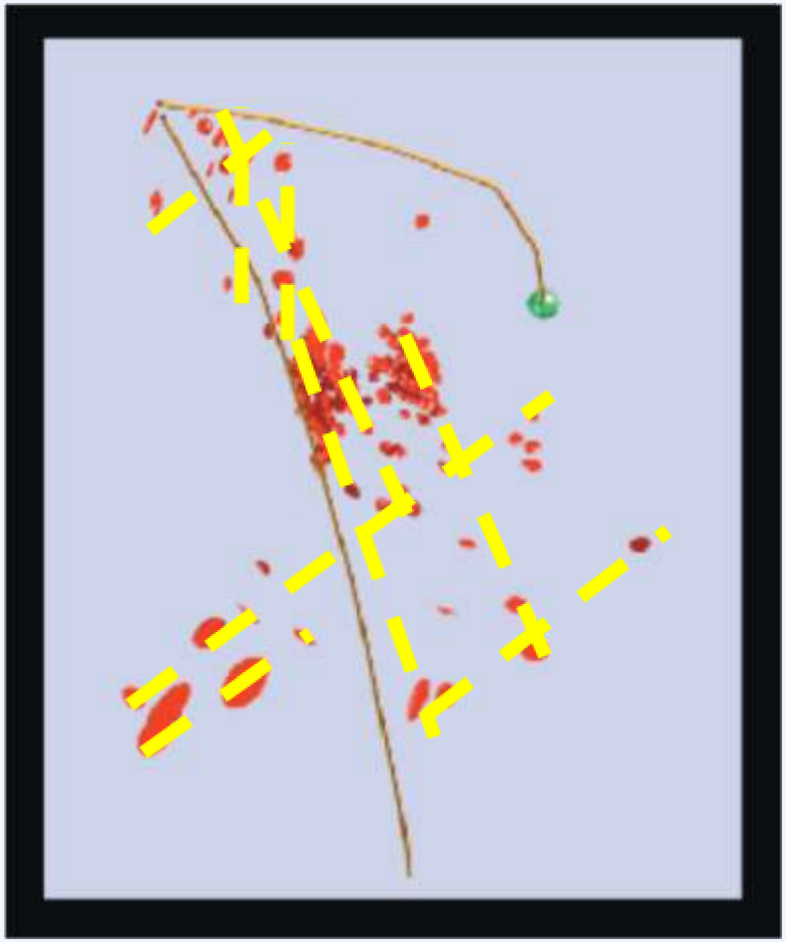
diffusivity major axes & lag-0 PC1 on fault traces



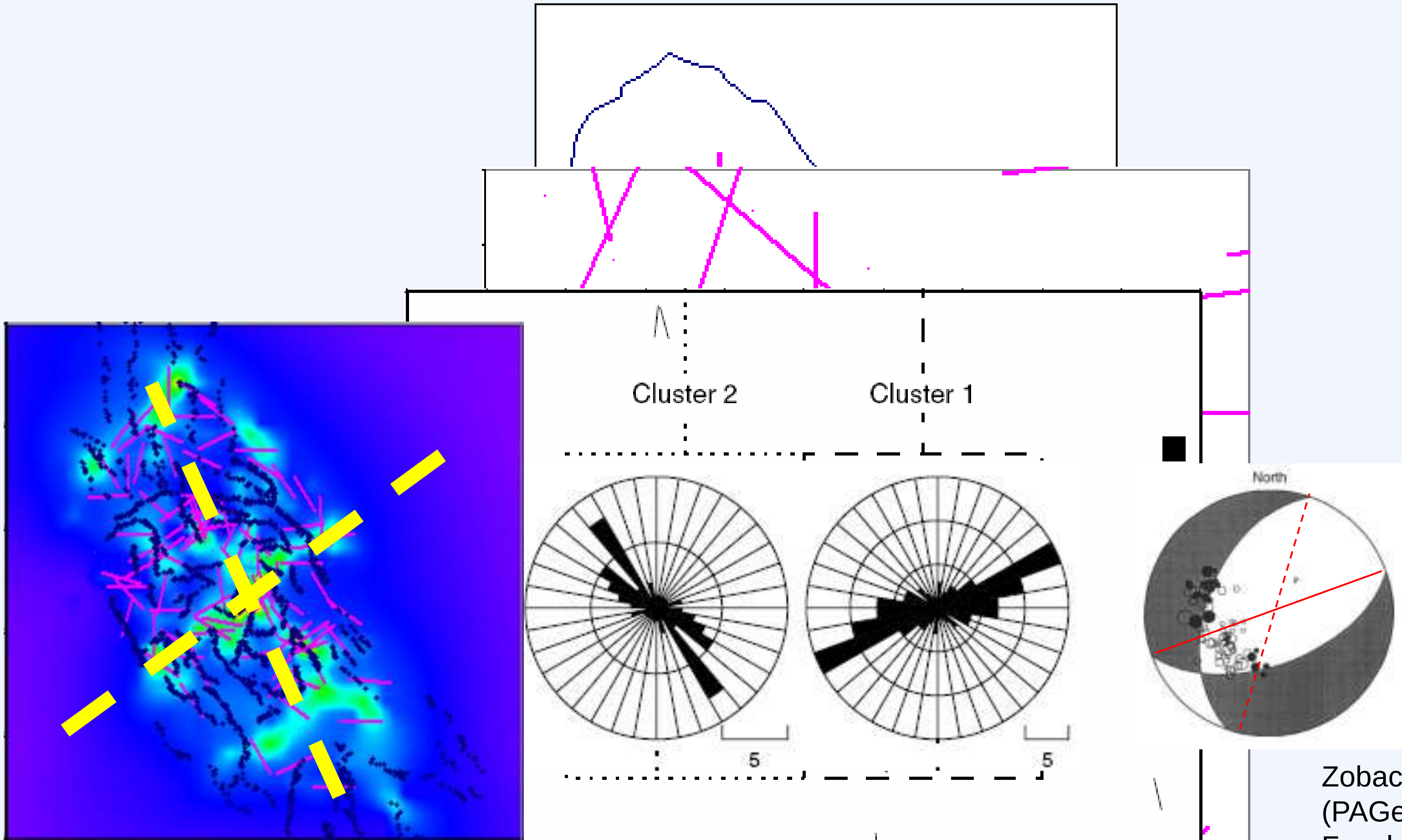
diffusivity major axes on induced inelastic shear strains (VISAGE™)



Valhall field: Microseismic emissions vs rate diffusivity trends



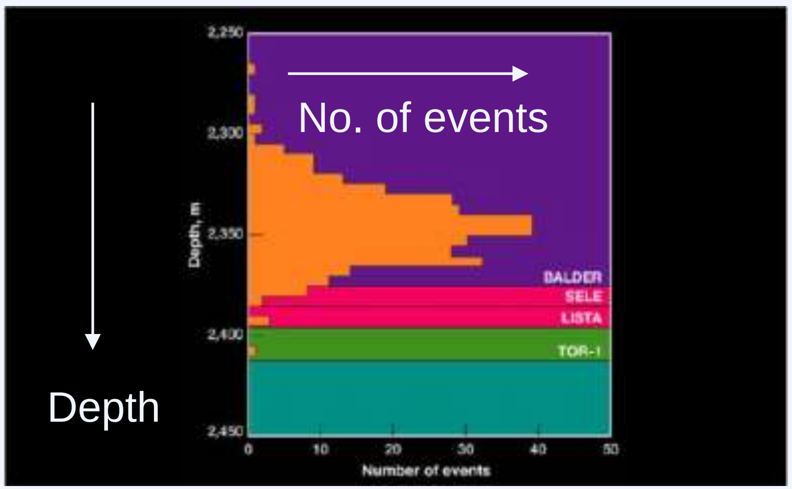
Valhall: Microseismic events and interpreted diffusivity axes from rate correlations

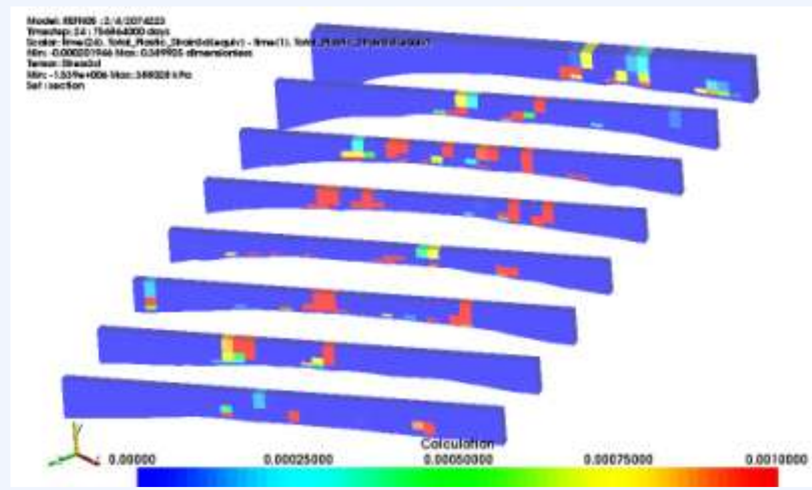


Fast shear waves = fracture strikes
Teanby et al. (GJI 2004)

Zoback & Zincke (PAGeophys, 2002)
Focal mechanism: normal slip

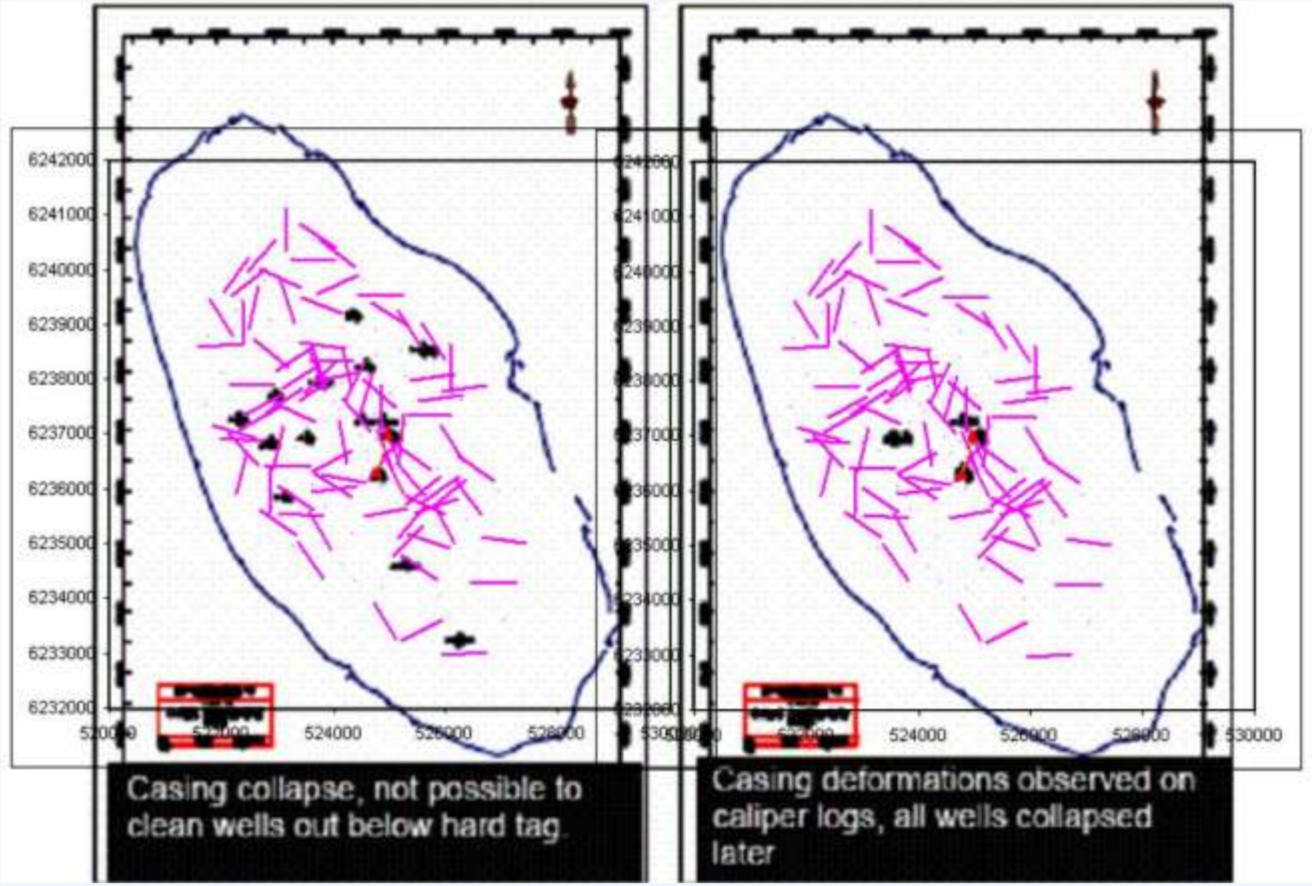
Valhall: Microseismicity and modelled strain due to depletion (VISAGE coupled model)





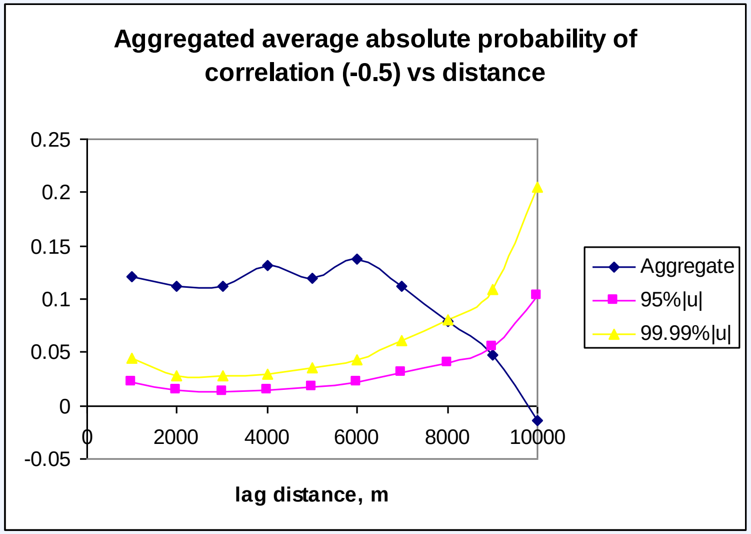
Total inelastic strain in layer above reservoir

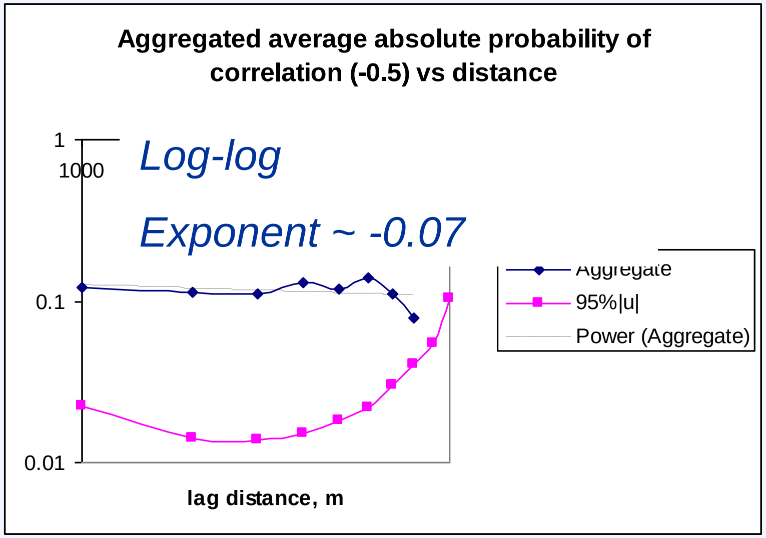
Valhall: Diffusivity axes and casing collapse/deformation



Aggregated North Sea fields
- Long-range correlations (zero lag time)

(detrended rate data)





From Statistical Reservoir Model:

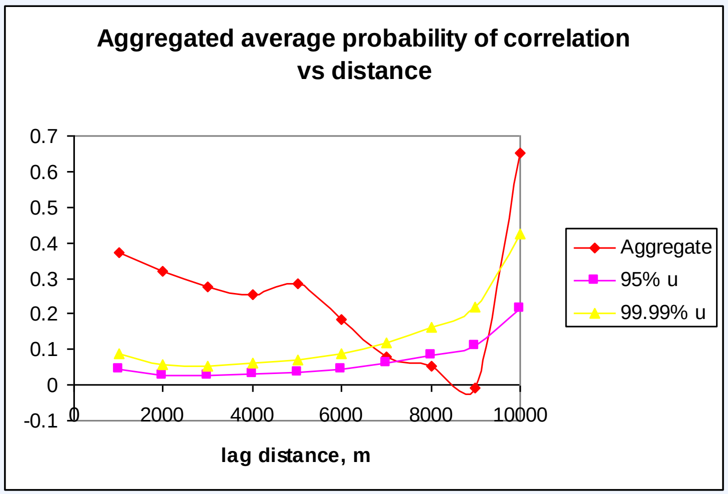
Mean exponent of ratio correlated/available wellpairs vs distance = -0.14

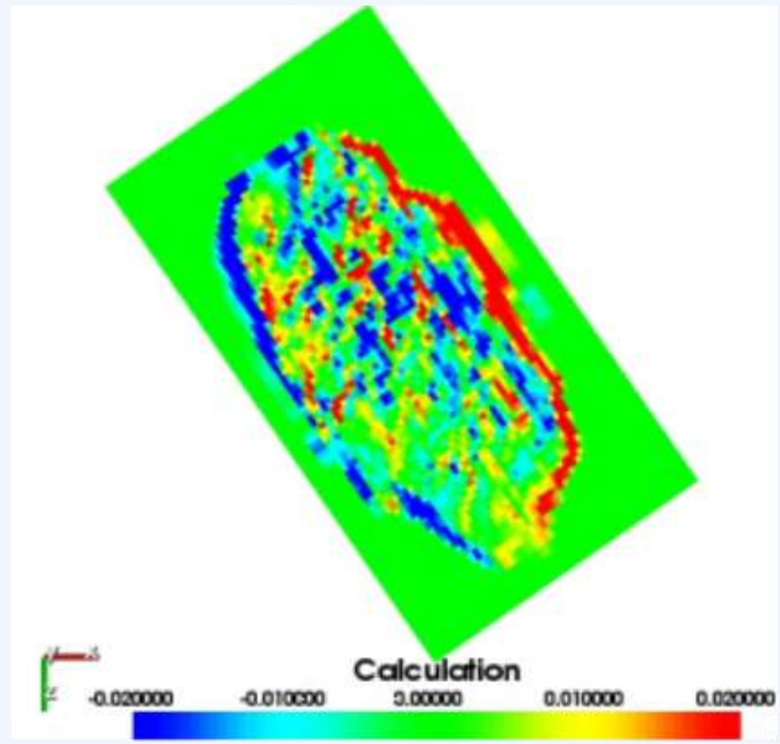
Average exponent of mean correlated distance vs time ~ 0.1

cf Fickian diffusion = 0.5 => NON-FICKIAN DIFFUSION

Boundary effect?

Raw rate data





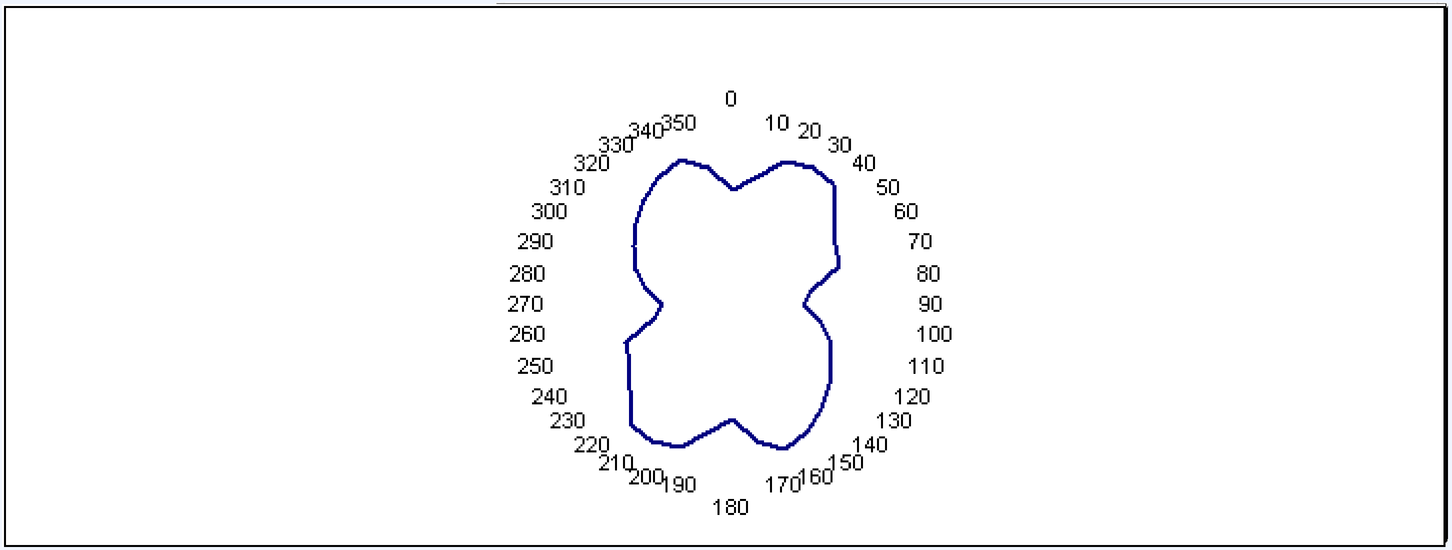
Coupled VISAGE model of Valhall: Normal shear strain in top reservoir layer

Orientational distribution of major diffusivity axes (aggregated fields)

Azimuthally smoothed

Shmax

Slip tendency of faults



North Viking graben

South Viking / Witch Ground grabens

Central graben

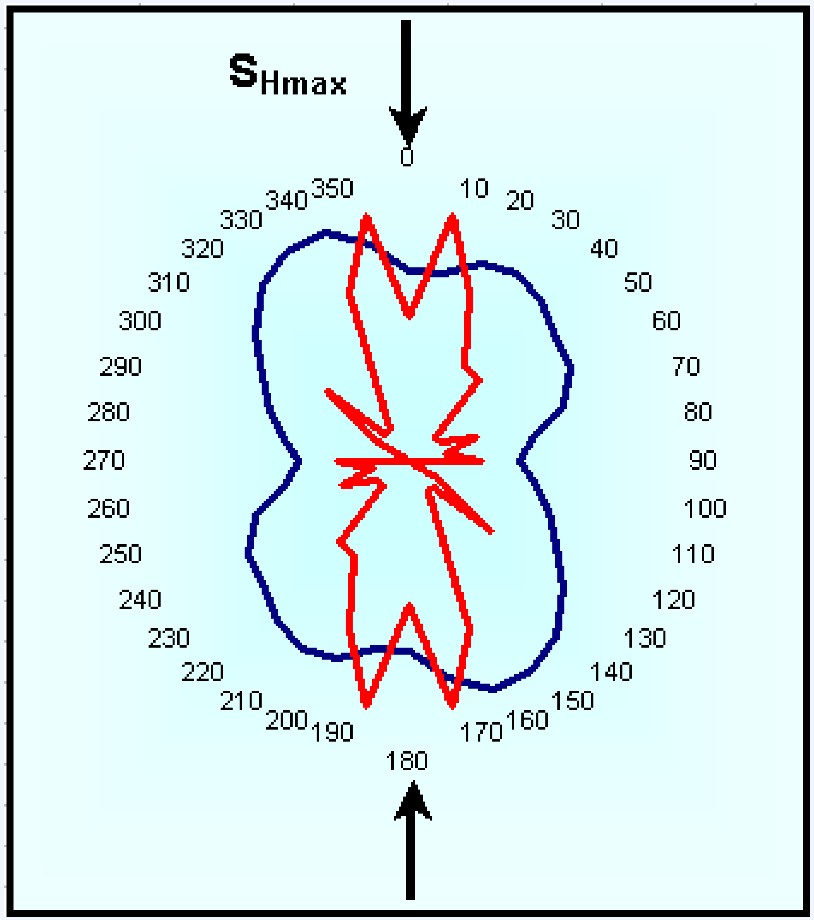
N — Highly anisotropic horizontal stresses — ~Isotropic horizontal stress — S

Strike-slip/thrust stress state

Normal stress state

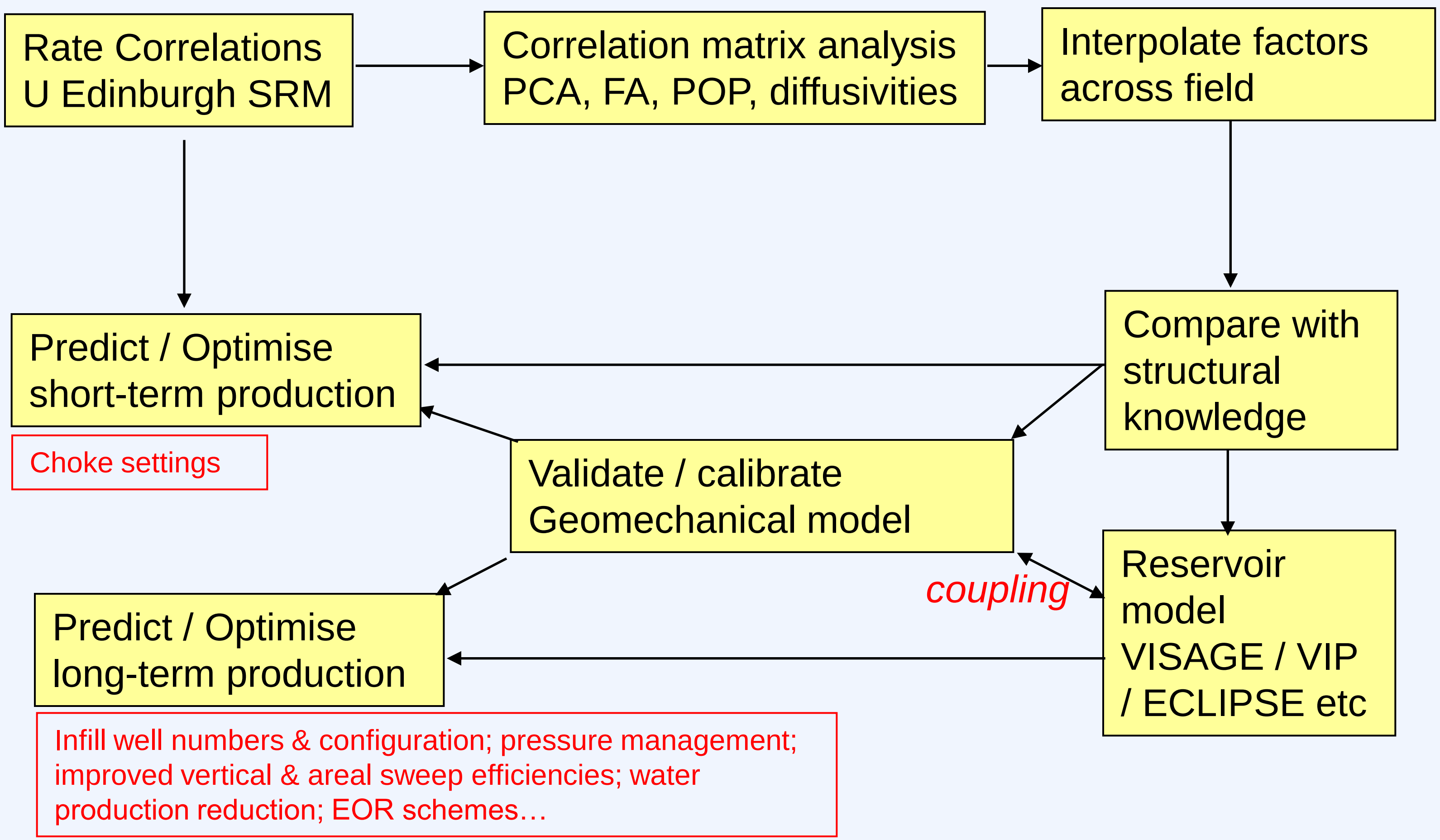
Orientational frequency distributions for 2 types of analysis of production histories both indicate the involvement of *shear slip* – even in ‘unfractured’ fields

major diffusivity axes for 4 ‘unfractured’ fields in North Sea



most favoured breakthrough directions for injected fluid in 47 ‘unfractured’ fields worldwide

Integration into reservoir management workflow



Messages

- Geomechanical effects appear to be influencing fluid behaviour in reservoirs worldwide (these effects appear to be commercially significant)
- These are associated with permeability changes
- Rate fluctuation analysis and geomechanical modelling can assist understand those effects >>>

Potential application of rate correlation analysis *Low cost; no acquisition*

1. Indicator of reservoir communications, complementary to geological model, microseismicity, seismic anisotropy, 4D seismic, well test permeabilities (mutual validation & calibration).
2. Time-lapse changes in communications .
3. Calibration of geomechanical understanding /model
4. Short-term rate predictions
5. Rate optimisation

Acknowledgements

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COFFERS project, under the Industry Technology Facilitator (sponsors: Amerada Hess, BG Group, BP, Conoco-Phillips, DTI, Kerr-McGee, StatoilHydro, Shell and Total)

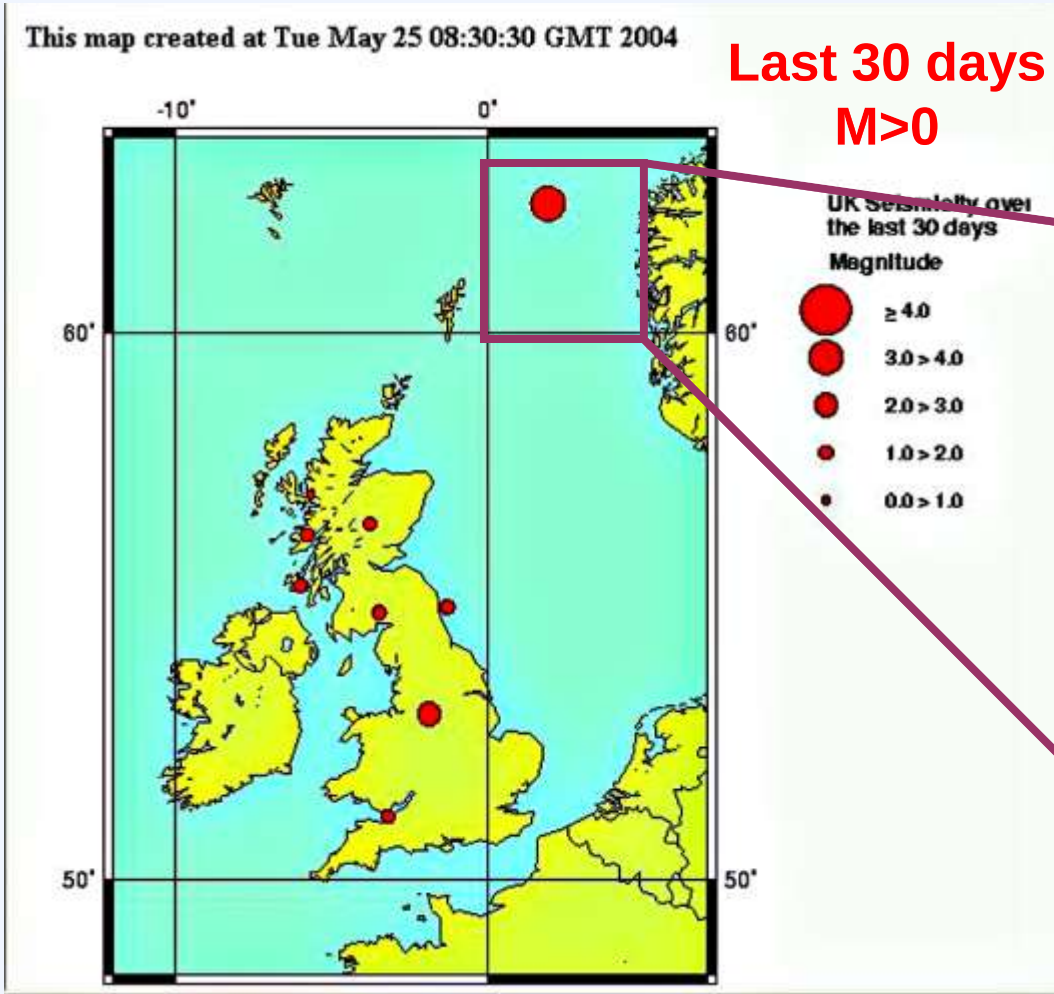
RESURGE project, sponsored by the

Technology Strategy Board

FIELD DATA provided by

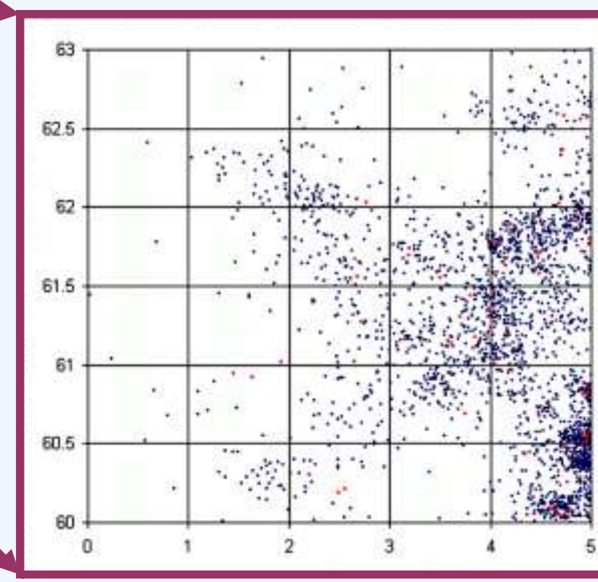
BP, Nexen, StatoilHydro

The North Sea is seismically active



Last 30 days
M>0

Last 30 years
M>0

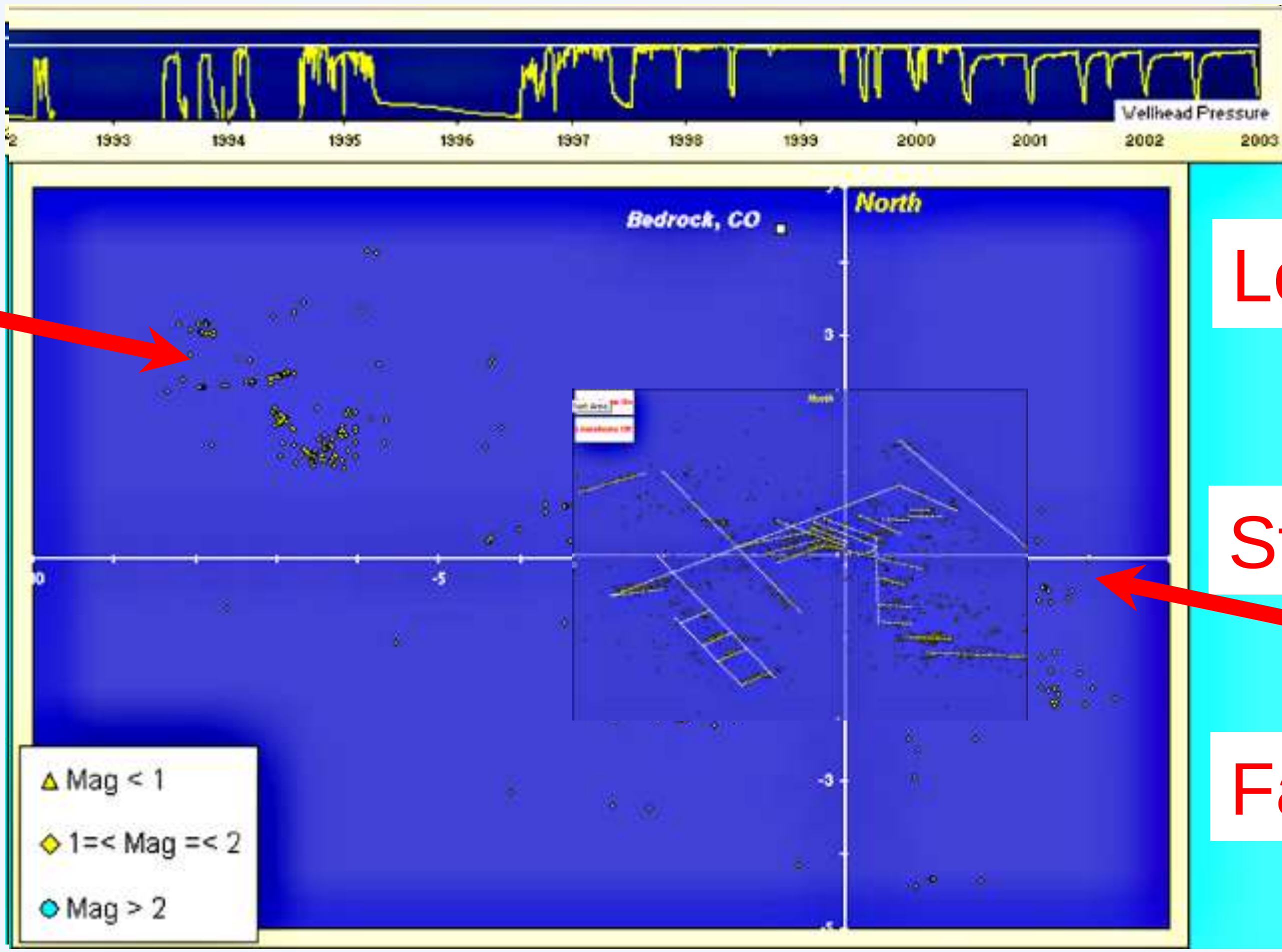


http://www.norsar.no/seismology

http://www.quakes.bgs.ac.uk/monthly_map.html

Progress towards a critical state: manifest in microseismic emissions

e.g. Paradox Valley (courtesy of Ken Mahrer, US Bureau of Reclamation)



Long-term injection

Long-range

Stress-related

S_H (WSM)

Fault-related

Induced seismicity

Microseismicity in Ekofisk

(Maxwell & Urbacic, The Leading Edge, June 2001)

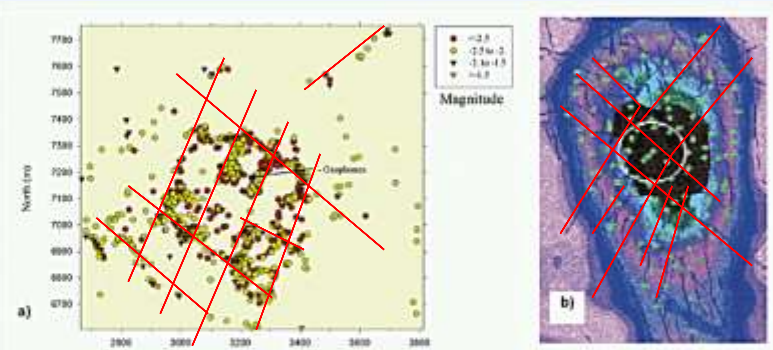
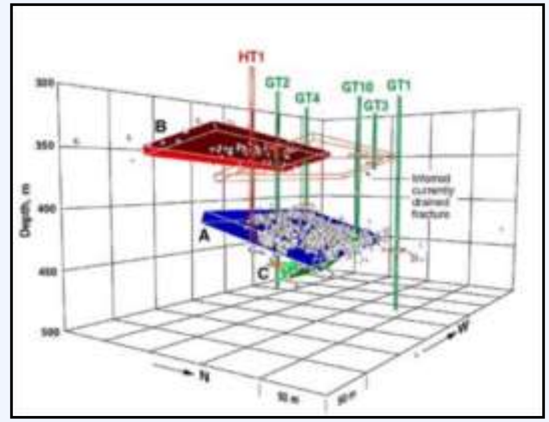


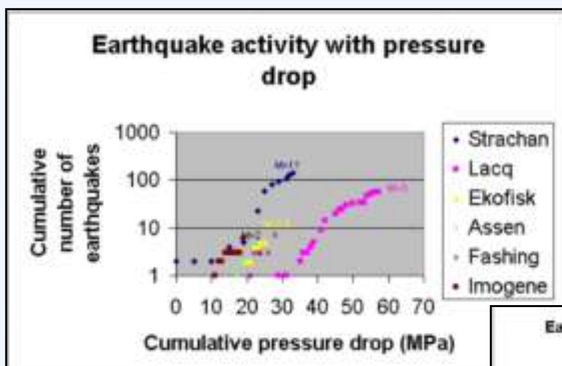
Figure 3. (a) Microseismicity recorded at Ekofisk with event locations scaled by magnitude. (b) Structural map of Ekofisk showing the gas cloud (black), major faults, and the region of microseismic detection (white circle). Note the preferred orientation of major faults in a NW-SE and NNE-SSW direction, which is similar to the orientation apparent from lineations of microseismic events.

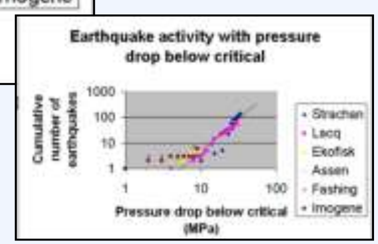
Productive fracture geometry from microearthquake locations

(Los Alamos NL from Clinton Co KY)



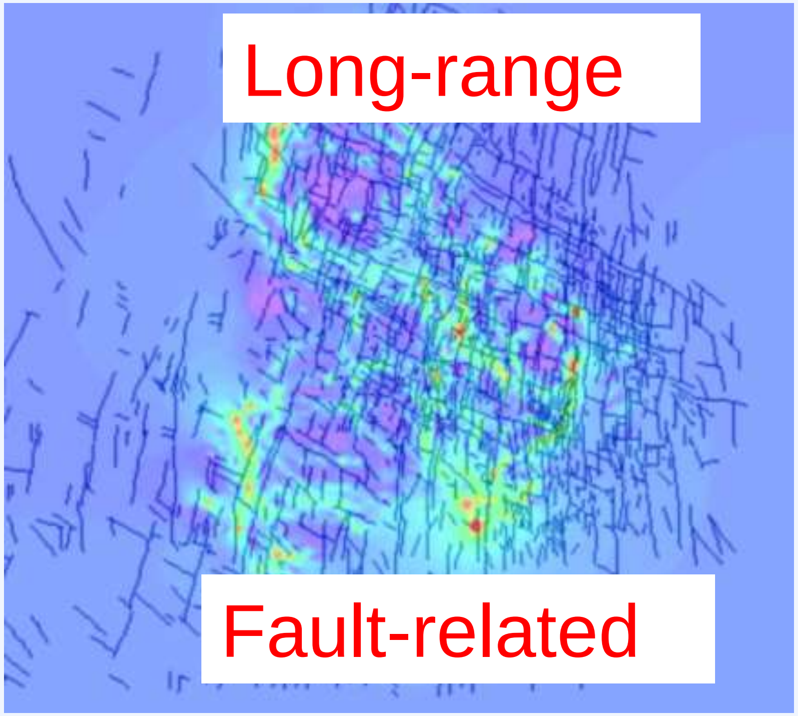
Seismicity induced by hydrocarbon extraction



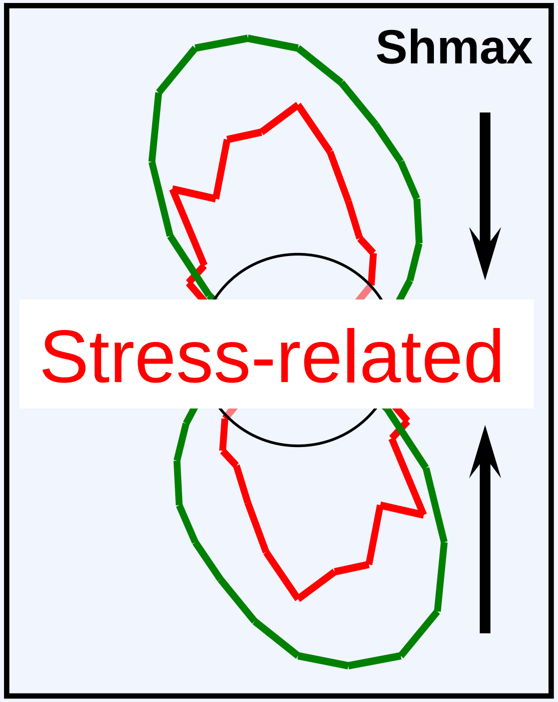


After Grasso & Sornette (1998)

General characteristics of rate correlations (Spearman rank)

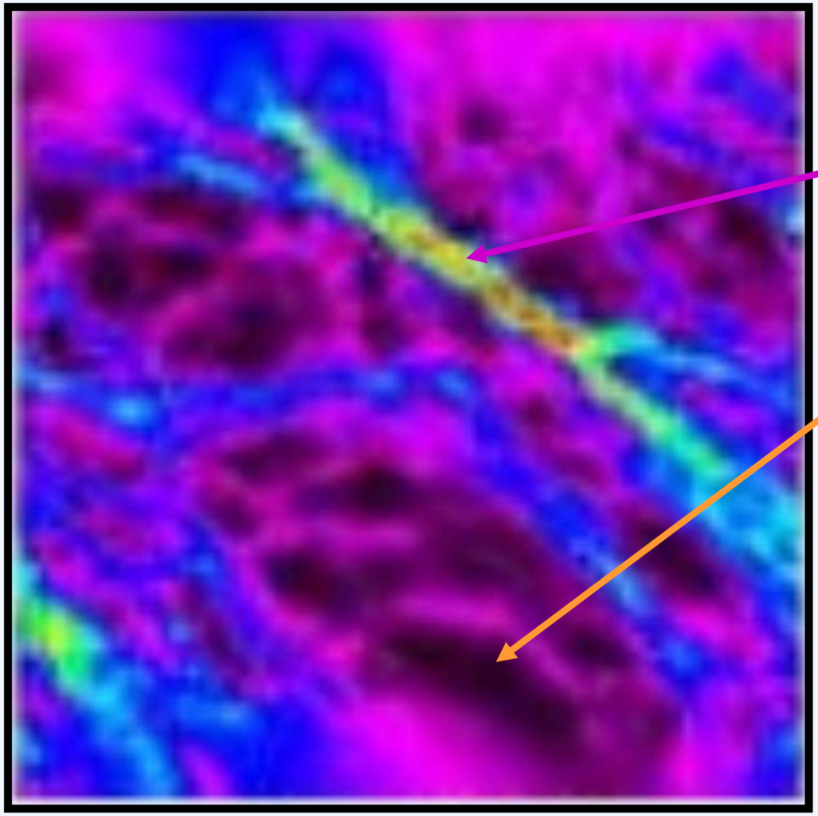


First principal component of matrix of rate correlations between all wells in field B – independent mode 'explaining' largest proportion of fluctuation variance



Raw rate fluctuations
Detrended rate fluctuations
__ zero correlation

Even in a state of SOC, not all lithosphere is at critical threshold



At criticality

Below criticality

=> not all samples will show characteristics of SOC/inherent stresses

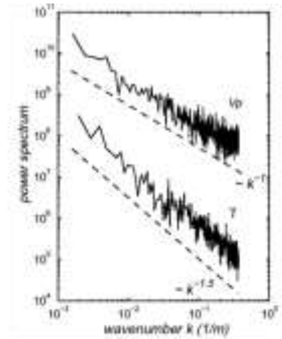
Further theoretical support

Power laws (indicative of criticality)

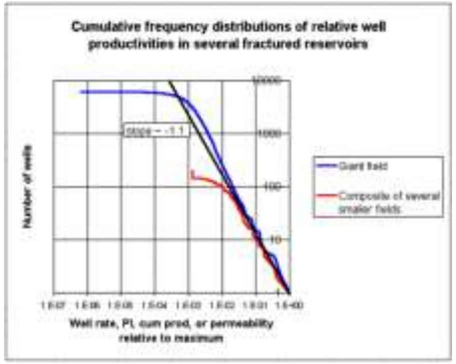
- Well logs (many properties; crystalline & sedimentary rocks) show spectral densities ~

$$\frac{1}{k^{\beta}}, \beta < 2$$

(fBm with H < 0.5 anti-persistent)

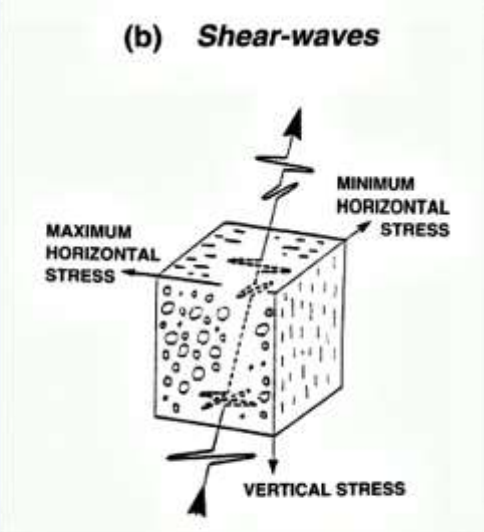


- Earthquake magnitude frequency distribution (Guthenburg-Richter)
- Fault & fracture length & displacement frequencies, spatial patterns
- Permeabilities in fractured reservoirs



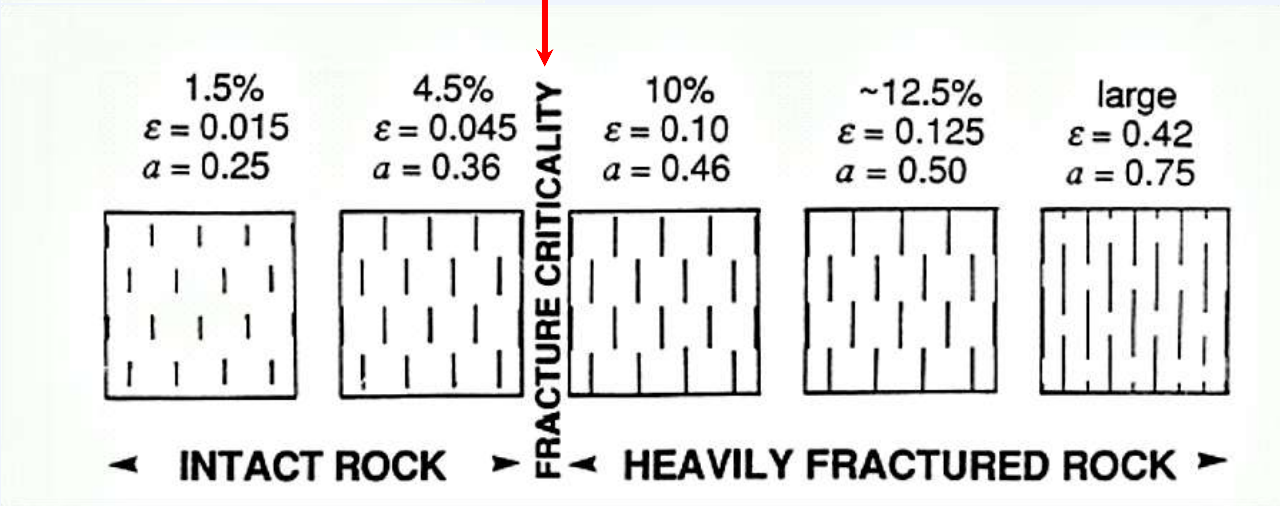
- Entropy is insensitive to energy in earthquake statistics (Main & AlKindy, 2002)

Shear wave splitting indicates fracture density near critical

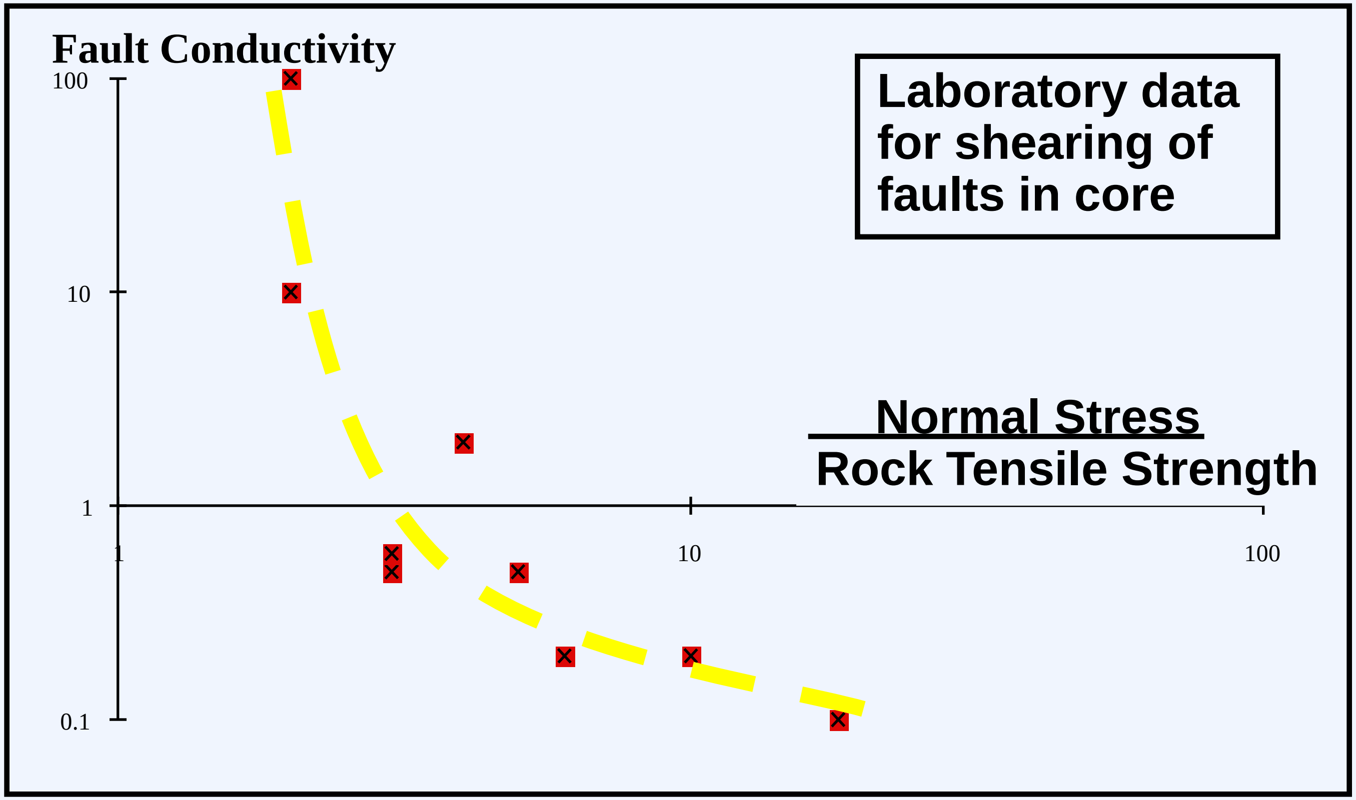


Stuart Crampin, Implications of rock criticality for reservoir characterization Journal of Petroleum Science and Engineering 24 1999 29–48

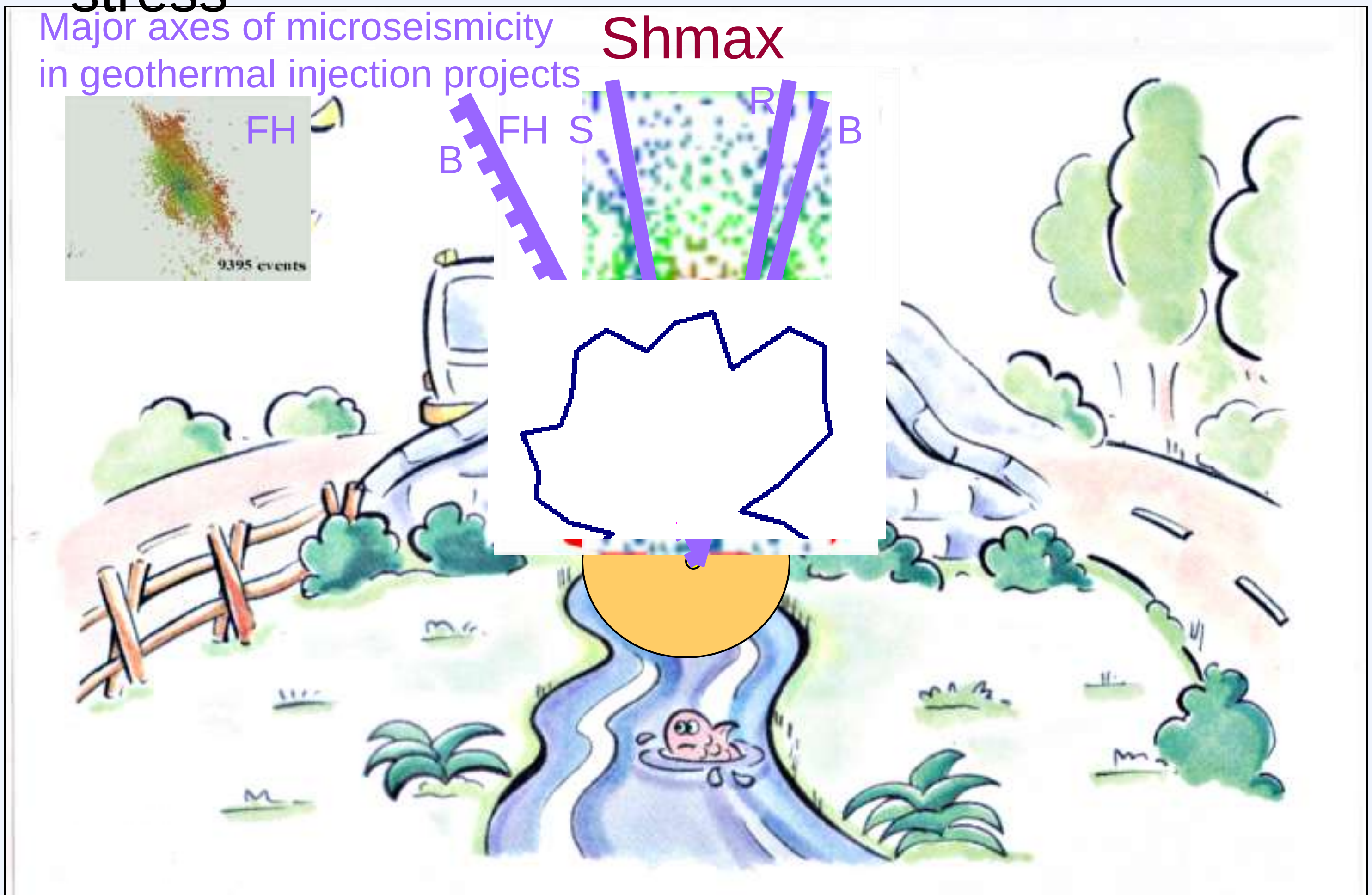
Most frequent densities



Fault conductivity and stress



Shear bands at small angles to max horizontal principal stress



Ito & Zoback, 3rd Euroconference on Rock Physics & Rock Mechanics, Nov 2000

Anisotropic stress state

Field data on preferred flow directionality

Modelled shear bands

Microseismic clouds

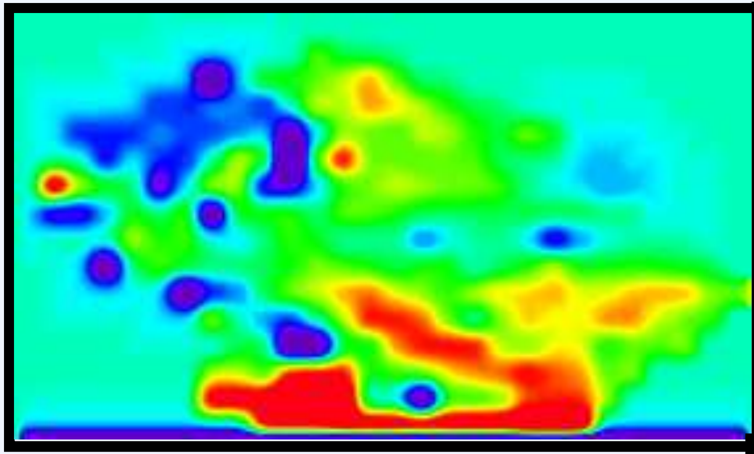
Orientational distribution of rate diffusivities

Shear failure sub-parallel to Shmax

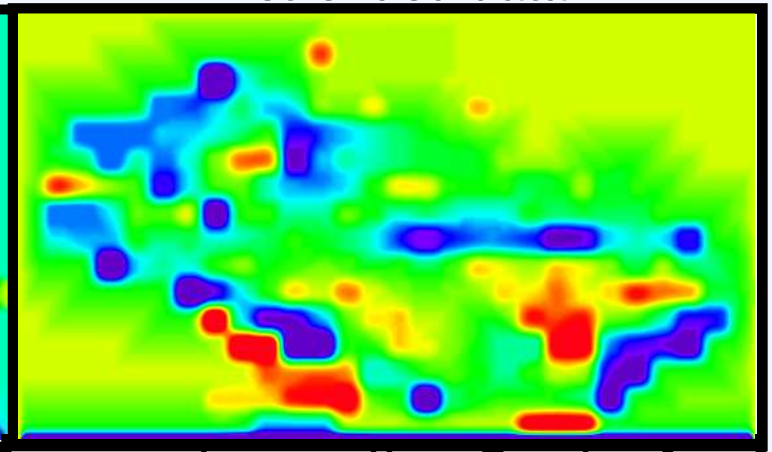
Cooling or pressurisation changes stress state

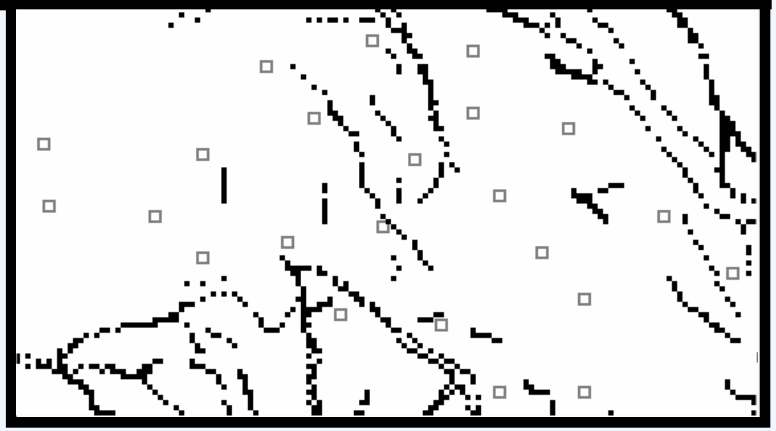
Field C - rate correlation coefficients interpolated between well pairs

Raw data

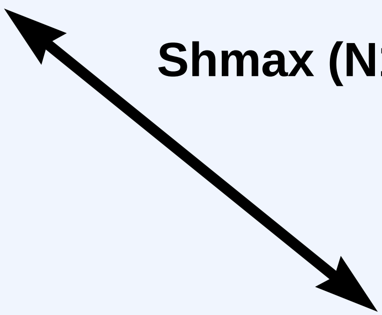


Detrended data





Faults & well locations to same scale



Shmax (N130E)