Observing reservoir dynamics and changing reservoir management

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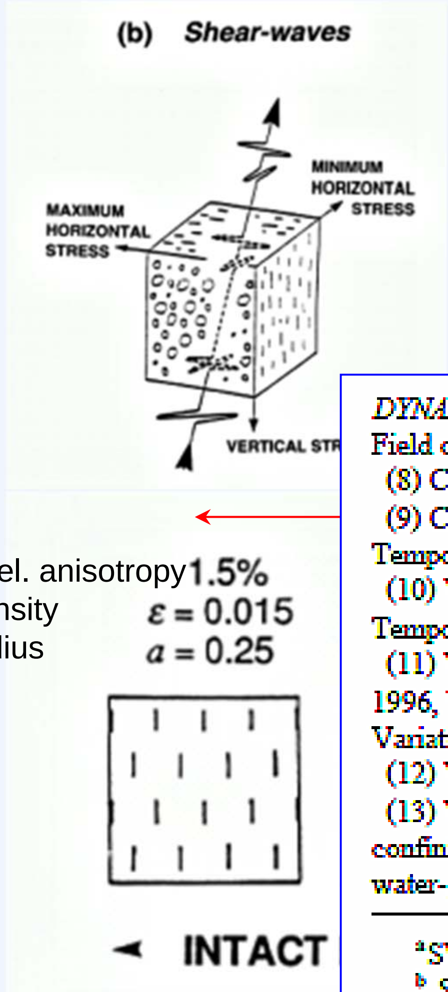
Talk outline

1. Stress-aligned microcracks at near-critical densities from shear-wave splitting
2. Flow Directionality & recovery in reservoirs
3. Other evidence for near-criticality of stress
4. Interwell correlations in rate fluctuations
    - General characteristics
    - Reservoir physics
    - Rate diffusivities
5. Results & microseismicity in Valhall
6. Aggregated results from 6 North Sea fields
    – consistency with 1. and 2.
7. Effect on recoveries – field data
8. Conclusions

Approximately chronological

Shear wave splitting indicates stress-aligned microcrack / fractures near critical density

Stuart Crampin et al.
http://www.geos.ed.ac.uk/homes/scrampin/opinion/

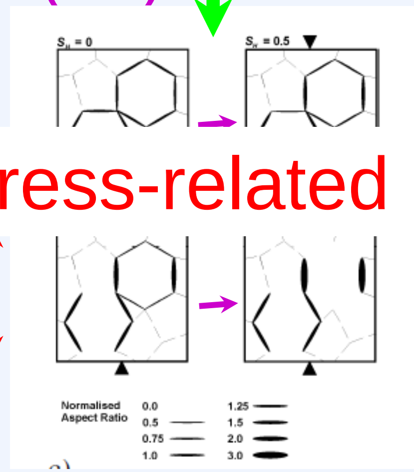


S-wave vel. anisotropy
Crack density
Crack radius

Anisotropic PoroElastic model (APE)

Shmax

Shmin



Stress-related

Increasing differential horizontal stress

DYNAMIC OBSERVATIONS

Field observations of SWVA

(8) Changes in SWVA before and after pumping tests

(9) Changes in SWVA before and after CO_2-flood in oil field

Temporal changes in SWTD[b] before earthquakes

(10) Variations of time-delays before earthquakes

Tempo…

(11) … re 30th Sept., 1996, …

Variations of shear waves in laboratory stress-cells

(12) … uniaxial pressure)

(13) … cities to changes in confin… oil-, water-, and gas- (dry) saturations of sandstone cores.

Highly sensitive

Long-range

[a]SWVA — shear-wave velocity-anisotropy.

[b] SWTD — shear-wave time-delays.

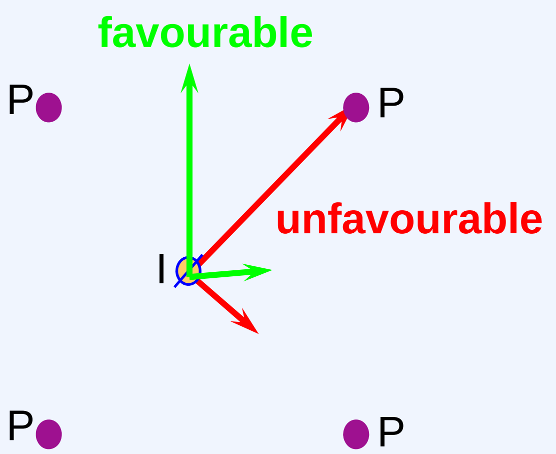
Field Directionality: The Prize – theory

Areal sweep efficiency and anisotropic permeability

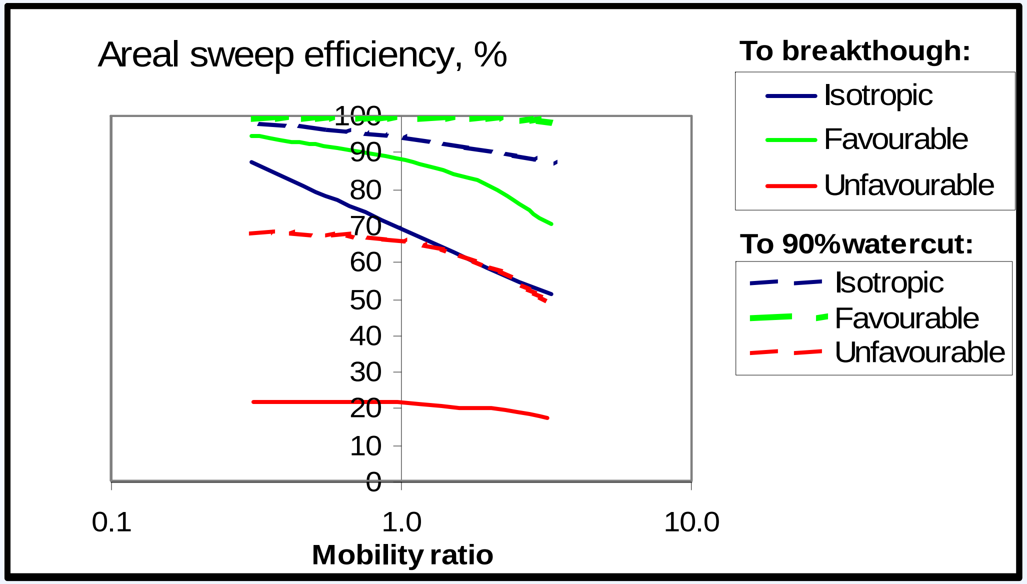
(classic: Caudle 1959)

For a 5 spot pattern of wells:

Permeability axes

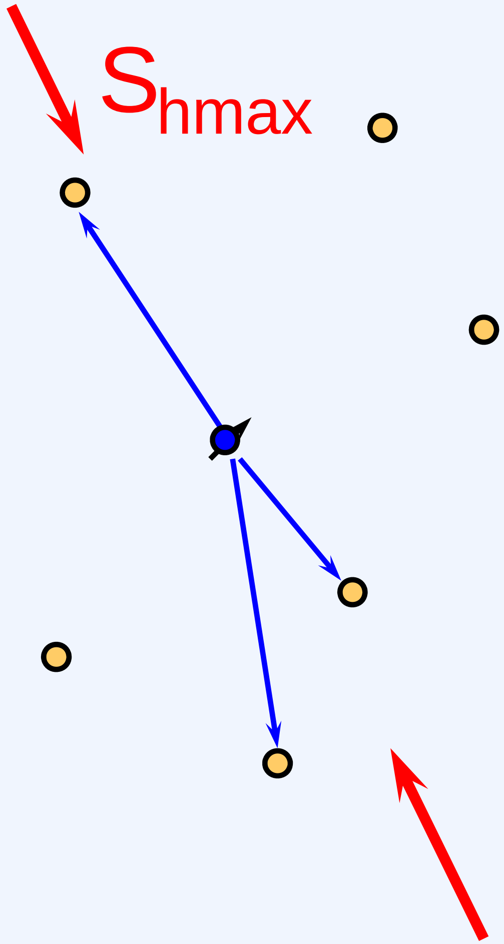


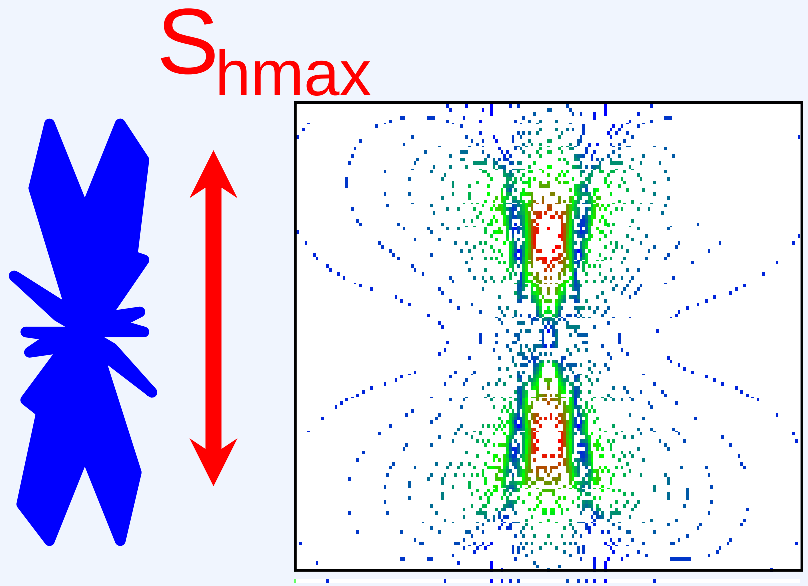
Physical model with Kmax/Kmin = 16



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

Flood directionality and Stress
Field data (“unfractured” reservoirs)





47 field cases (“unfractured”)

Numerical FE Modelling

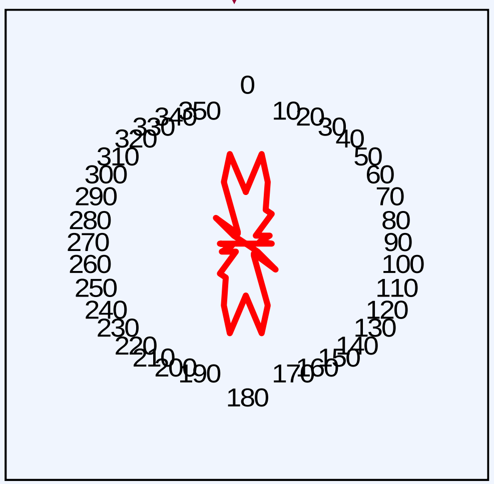
Flood Directionality & Stress State
Field evidence

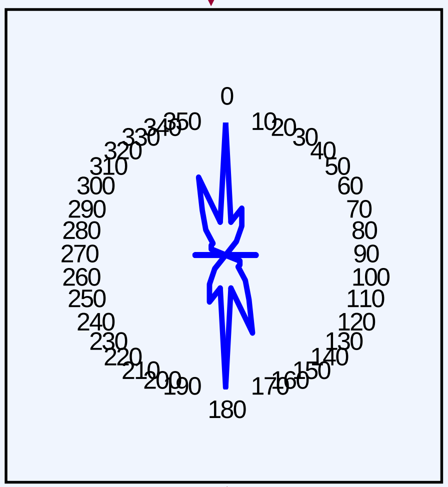
'Unfractured'
Reservoirs
(47 cases)

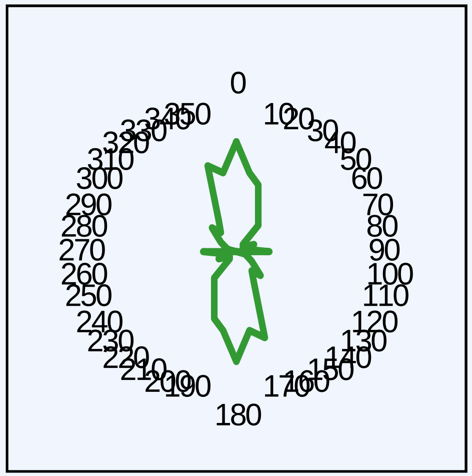
Shmax

'Fractured'
Reservoirs
(33 cases)

All
Reservoirs
(80 cases)





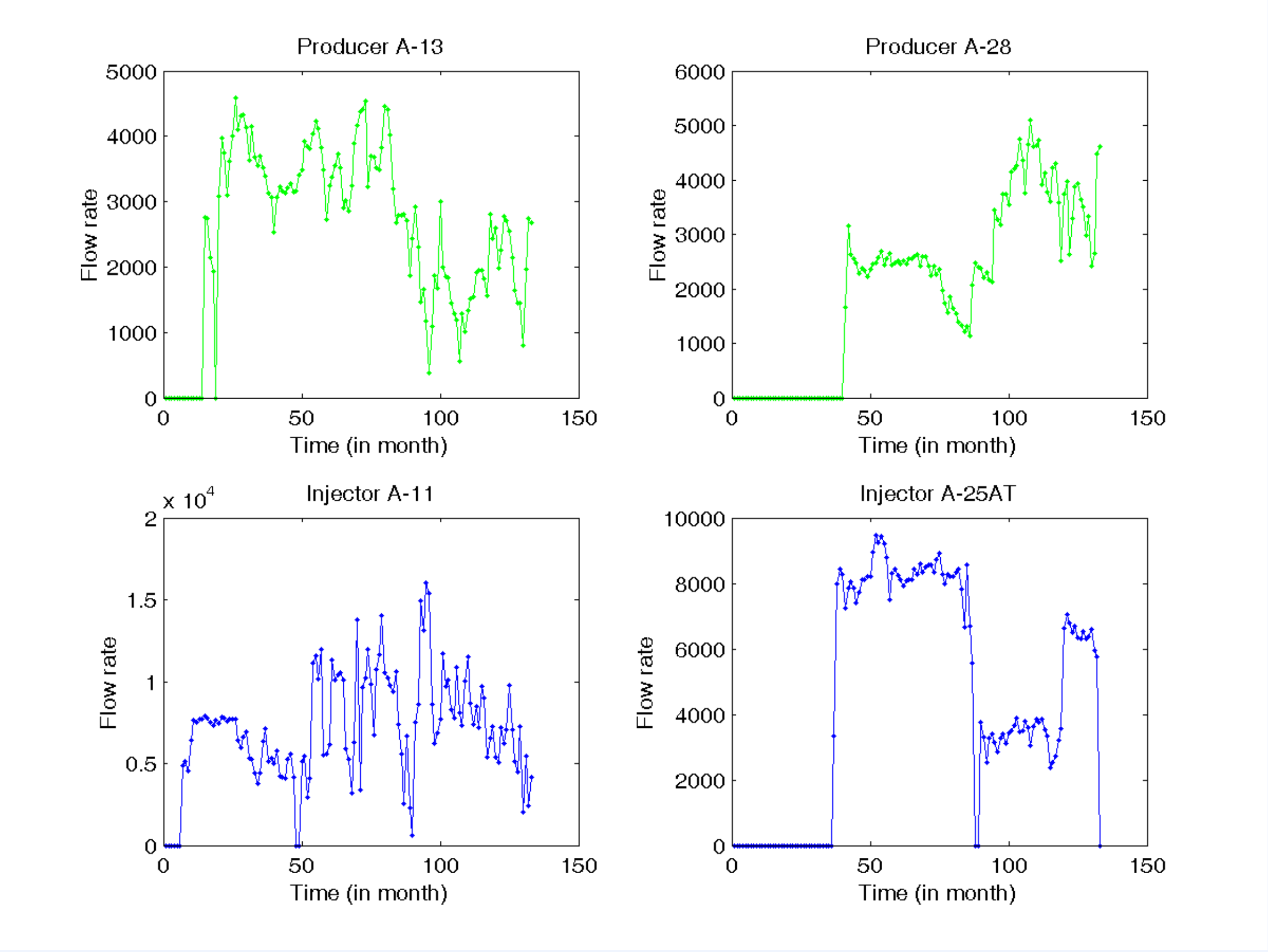


Finding Petroleum; 18 April 2012

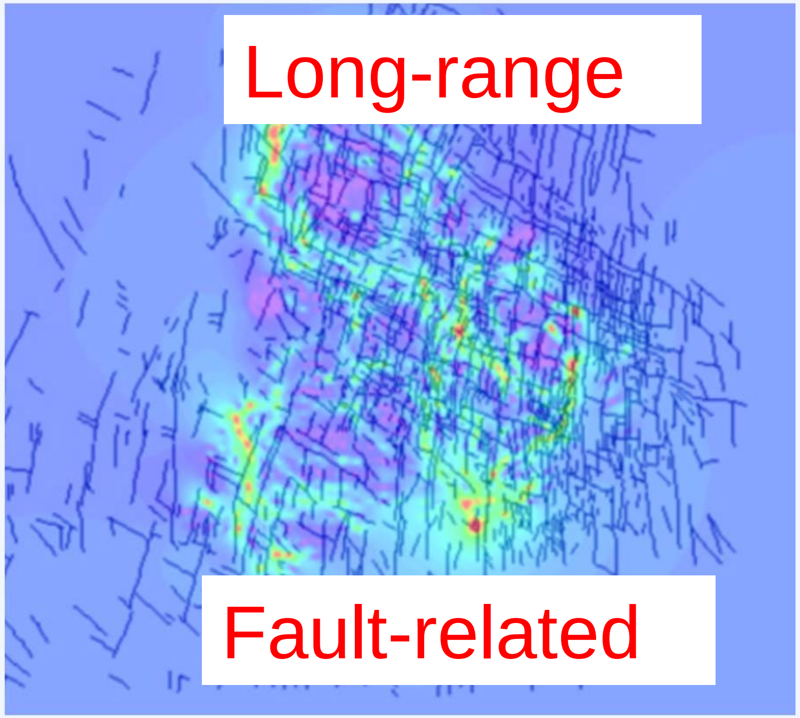
Flow rate fluctuations

Producers

Injectors

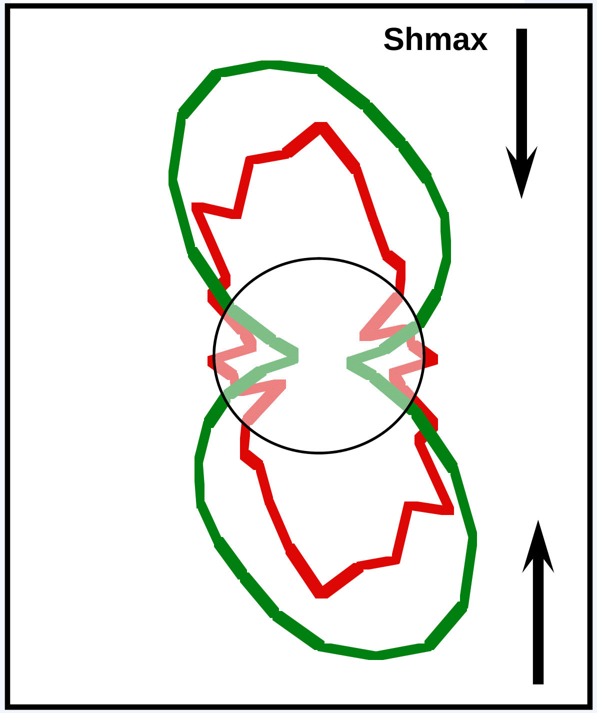


Interwell correlations between rate fluctuations - general characteristics



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

Stress-related

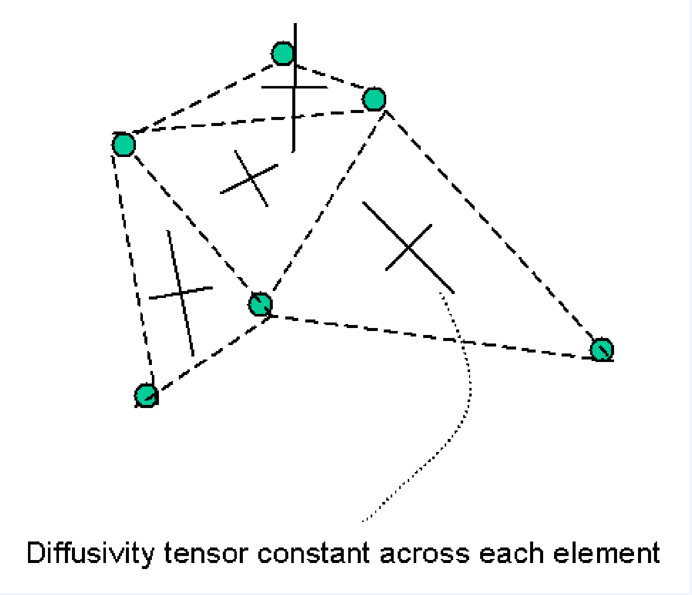


Injector-Producer pairs only
>0.5x10⁶ pairs; 8 field areas
broadband fluctuations
high frequency fluctuations
__ zero correlation

Reservoir physics

- Communications are not just Darcy fluid flow, but…
- …coupled fluid flow and geomechanics
    - incorporating pre-existing microcracks, fractures and/or faults
    - influenced by modern-day stress state
    - involving changing permeabilities
- … near a critical point
    - long-range interactions

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



For triangles between wells:

Extract tensors related to *diffusive* rate behaviour:

Takes some account of spatial relationship of wells & of time-behaviour of correlations.

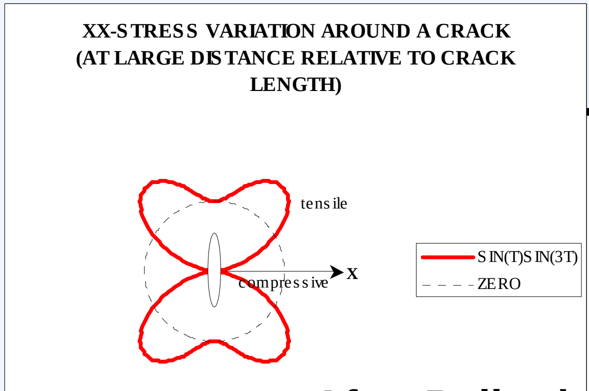
Case studies (6) in North Sea

Diffusivity of flow rates: orientational distributions relative to maximum horizontal stress

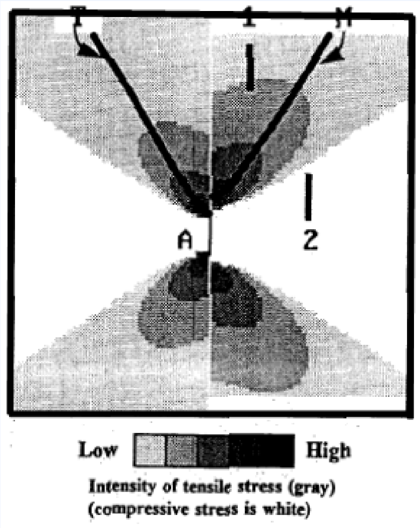
Highly anisotropic horizontal stresses
Strike-slip/thrust stress state

~Isotropic horizontal stresses
Normal stress state

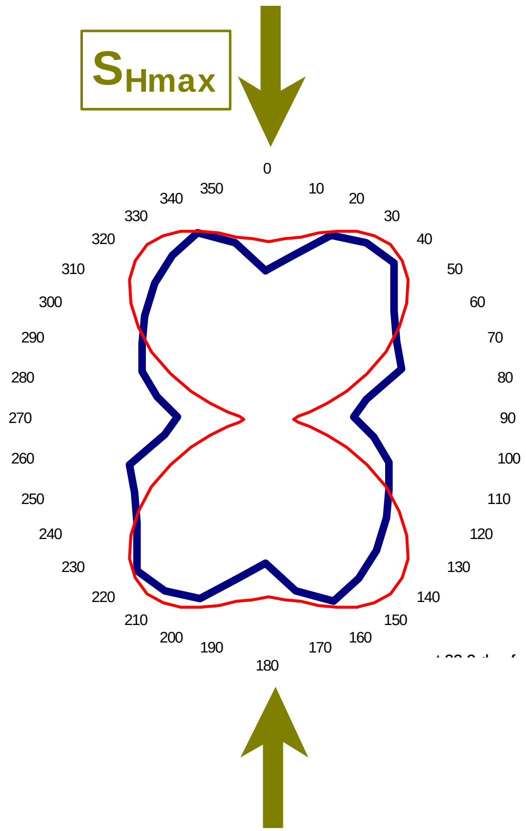
Aggregated orientational frequency distributions of major diffusivity axes - for 6 N Sea fields

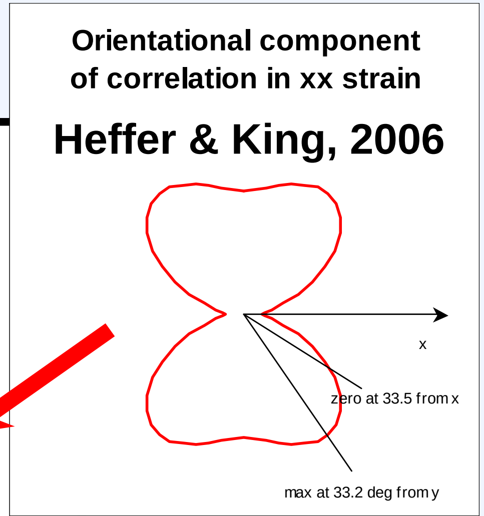


After Pollard



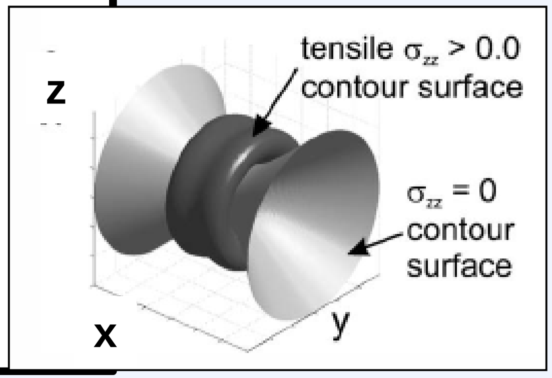
Reches & Lockner, 1994





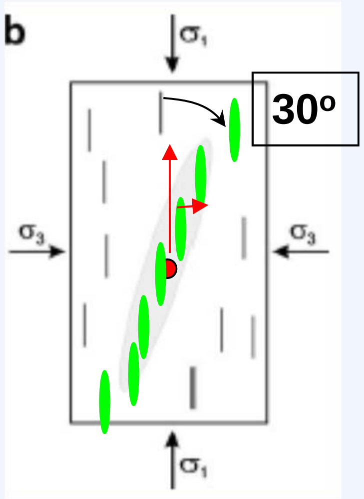
Heffer & King, 2006

Healey et al, 2006



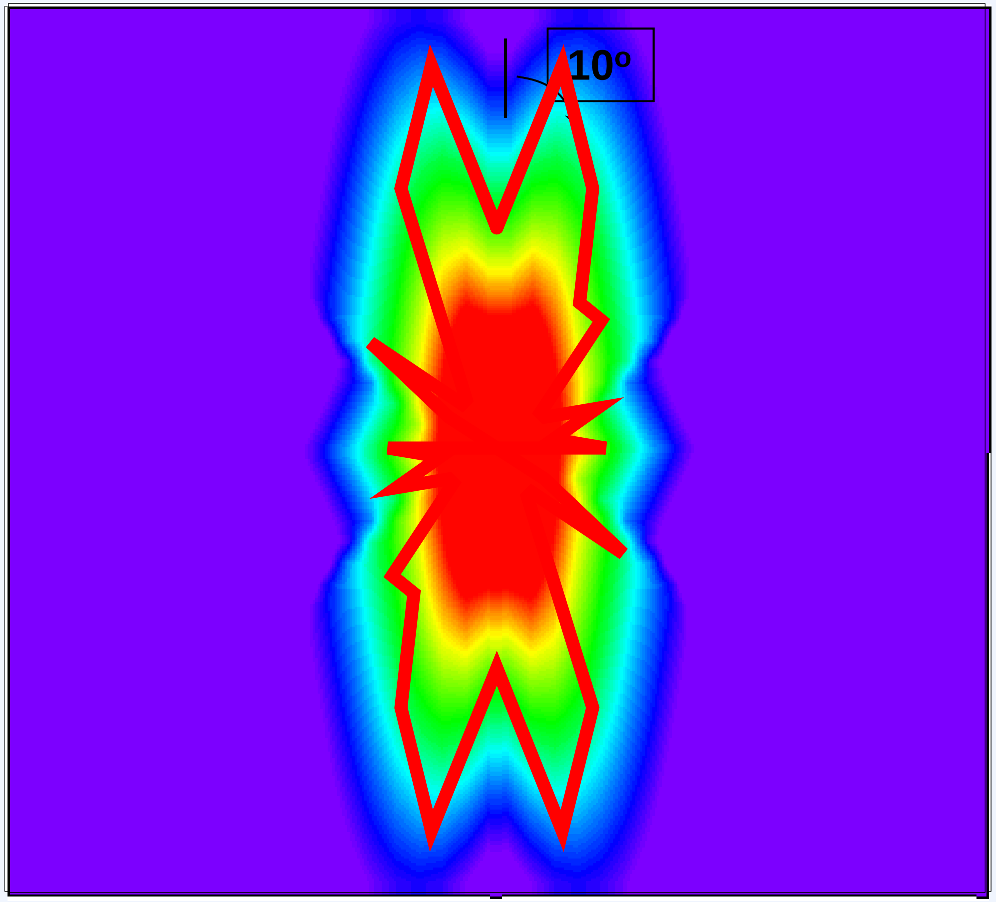
Flood progress through interacting fractures in matrix of medium permeability

permeability



Healey et al, 2006

Fracture dilation

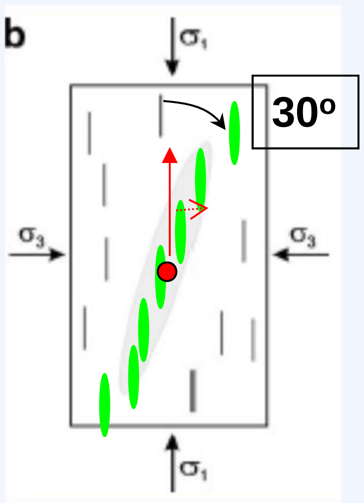


most favoured breakthrough directions for injected fluid in 47 ‘unfractured’ fields worldwide

Min. path distribution around a well ~ isobars of pressure field. Equivalent to flood progression.

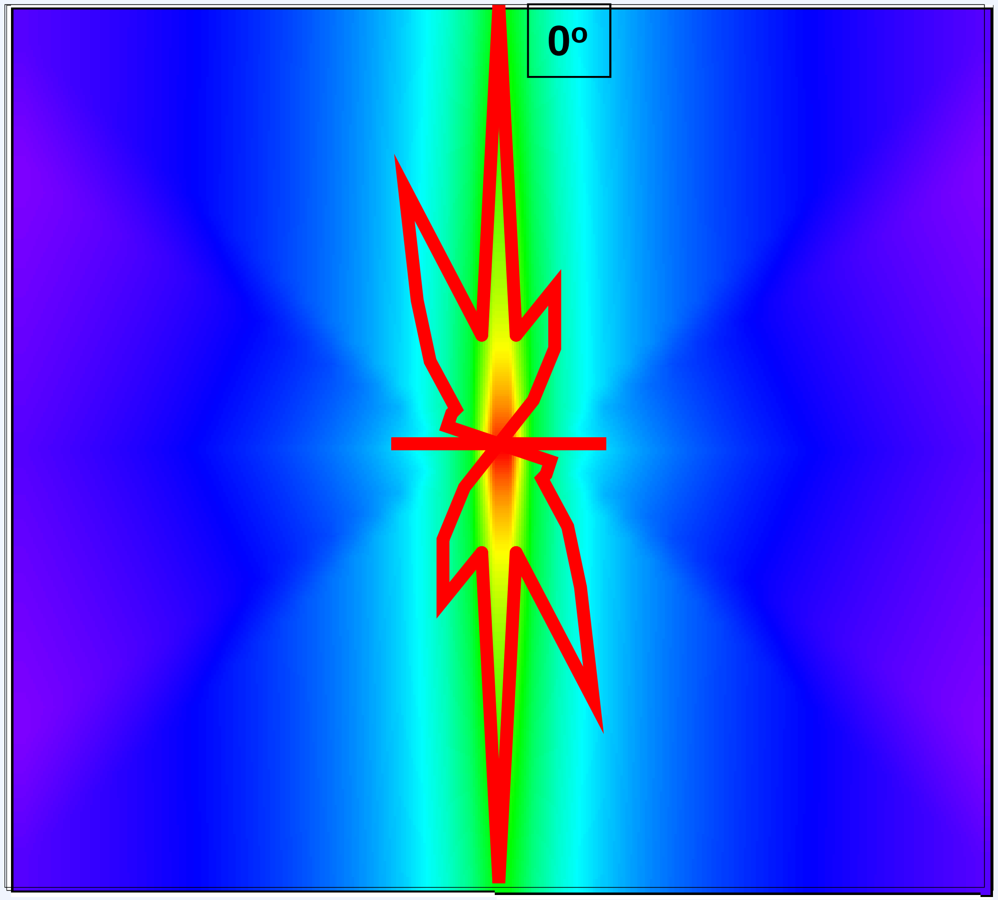
Flowstreams through interacting fractures in matrix of low permeability

permeability



Healey et al, 2006

Fracture dilation



most favoured breakthrough directions for injected fluid in 33 'fractured' fields worldwide

Min. path distribution around a well ~ isobars of pressure field. Equivalent to flood progression.

Possible mechanism (2): reactivation of polymodal faults

(Reches, 1978, 1983; Krantz, 1988, 1989)

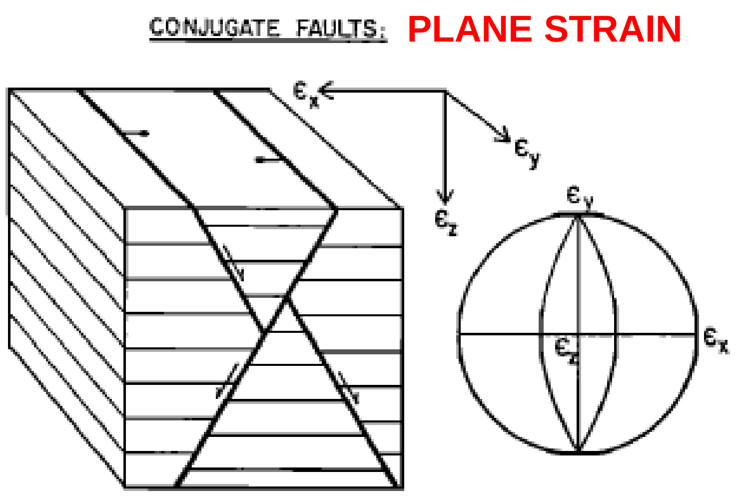


Fig. 1. Block diagram and stereonet showing the relationship of two conjugate fault sets to the principal strain axes. The two sets intersect parallel to the intermediate principal strain.

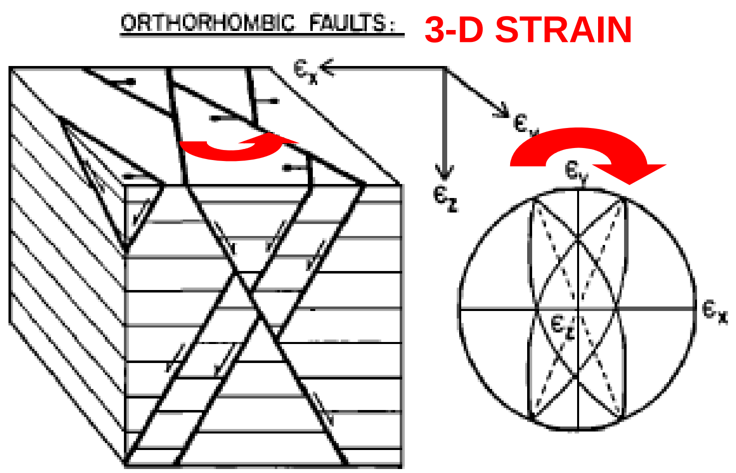
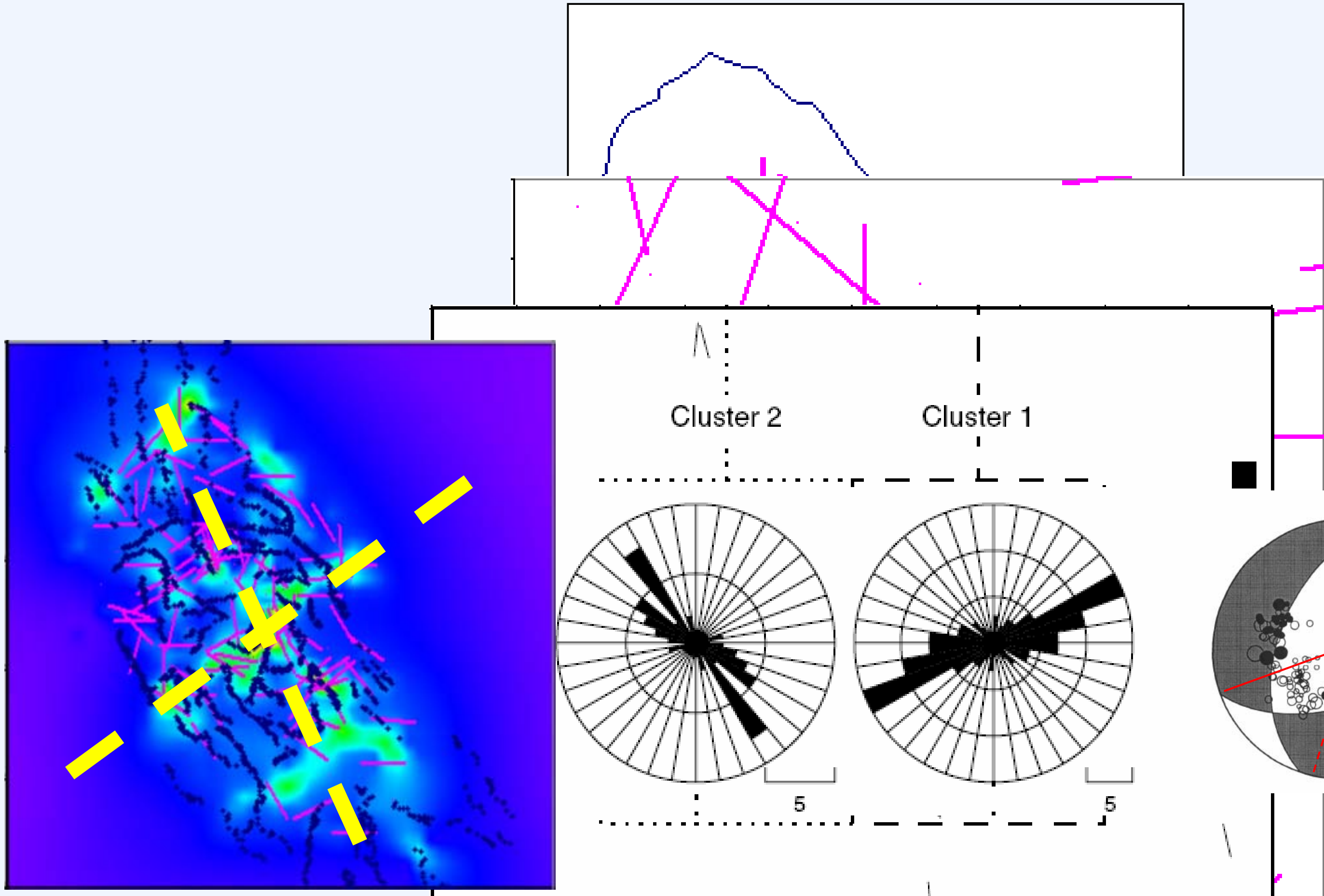


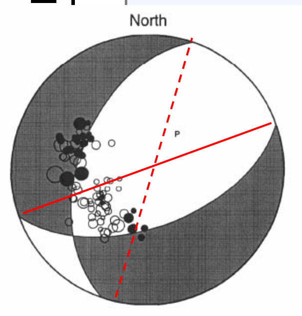
Fig. 2. Block diagram and stereonet showing the relationship of four orthorhombic fault sets to the principal strain axes. Reprinted with permission from the Journal of Structural Geology, volume 10, R.W. Krantz, Multiple fault sets and three-dimensional strain: theory and application, Copyright 1988, Pergamon Press PLC.

Dihedral angle related to ratio of intermediate and minimum extensional strains – related to local stress tensor

Valhall: Microseismic events and interpreted diffusivity axes from rate correlations

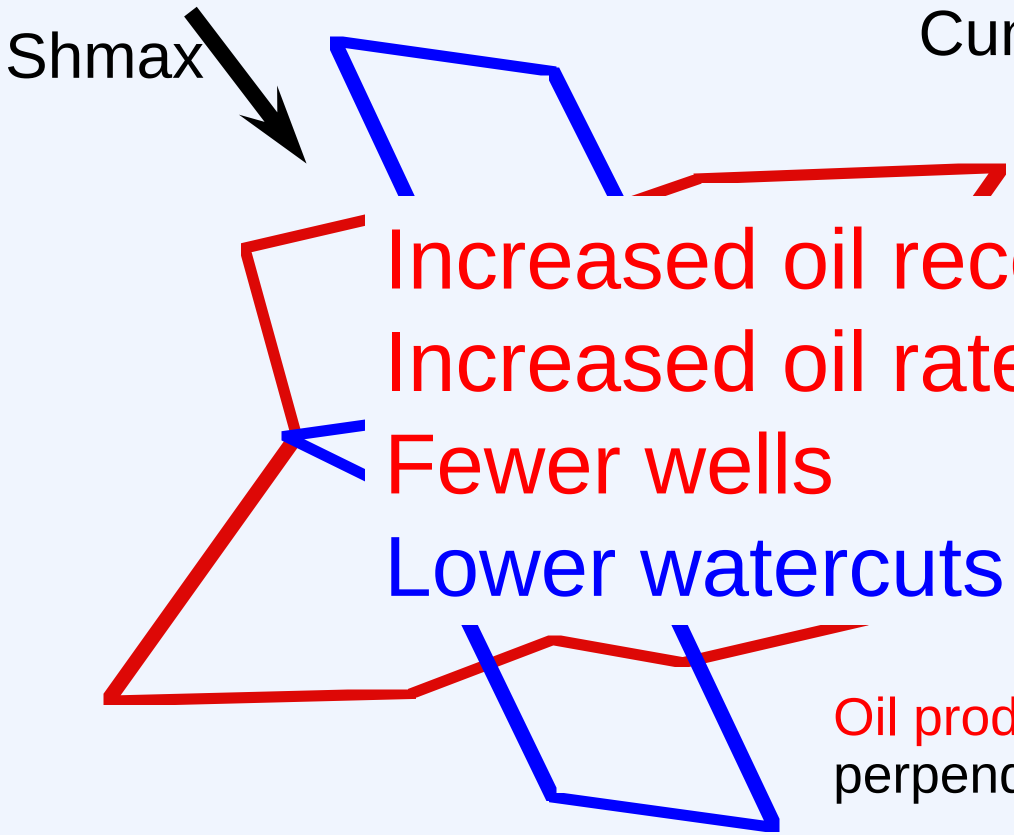


Fast shear waves = fracture strikes
Teanby et al. (GJI 2004)



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

The Prize – field data



Cumulative production per well

Oil

Water-oil ratio

Increased oil recovery
Increased oil rate
Fewer wells
Lower watercuts

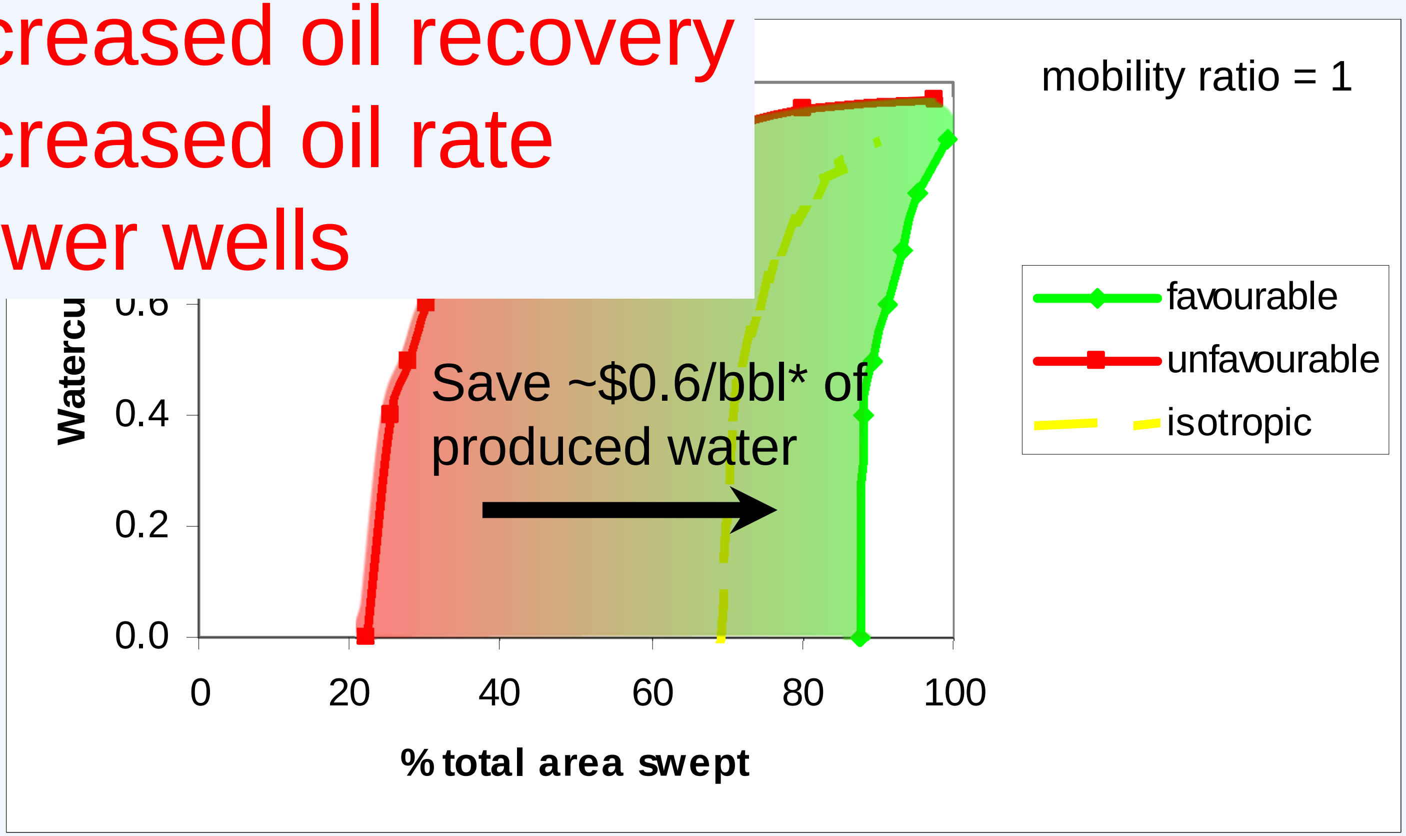
Oil production is greatest perpendicular to stress

WOR greatest sub-parallel to stress

The Prize – theory

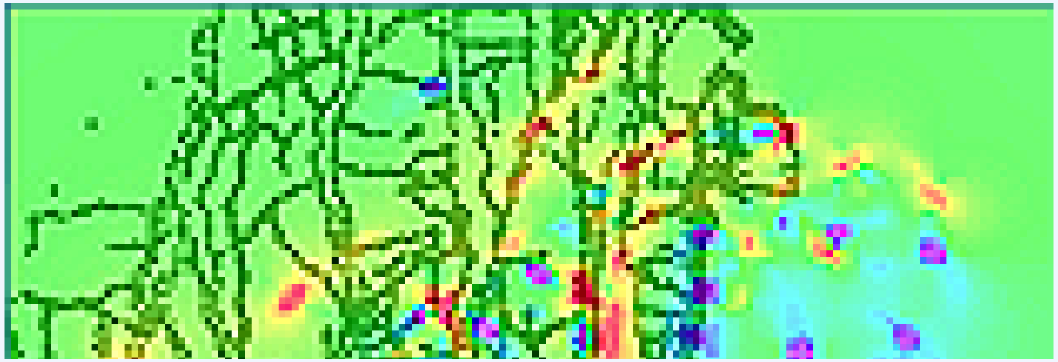
Lower watercuts

Increased oil recovery
Increased oil rate
Fewer wells

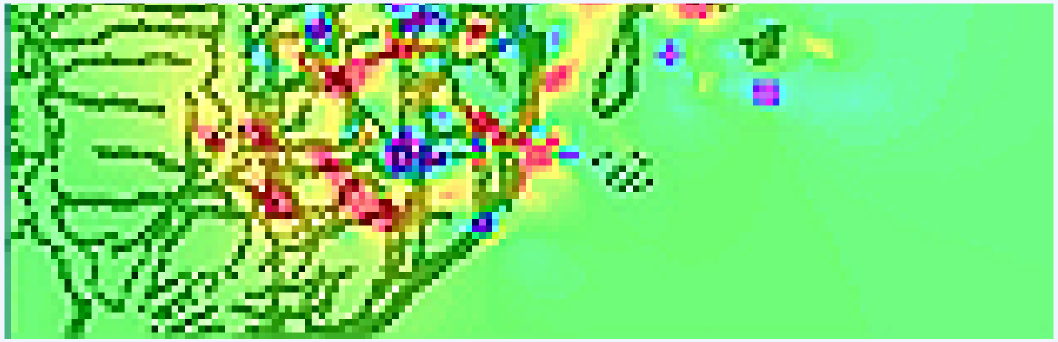


*SPE 73853 Khatib & Vermeek, 2002
e.g. $22million p.a. at 100,000 bwpd

Rate correlations can identify faults /fracture paths involved in the processes to aid reservoir modelling



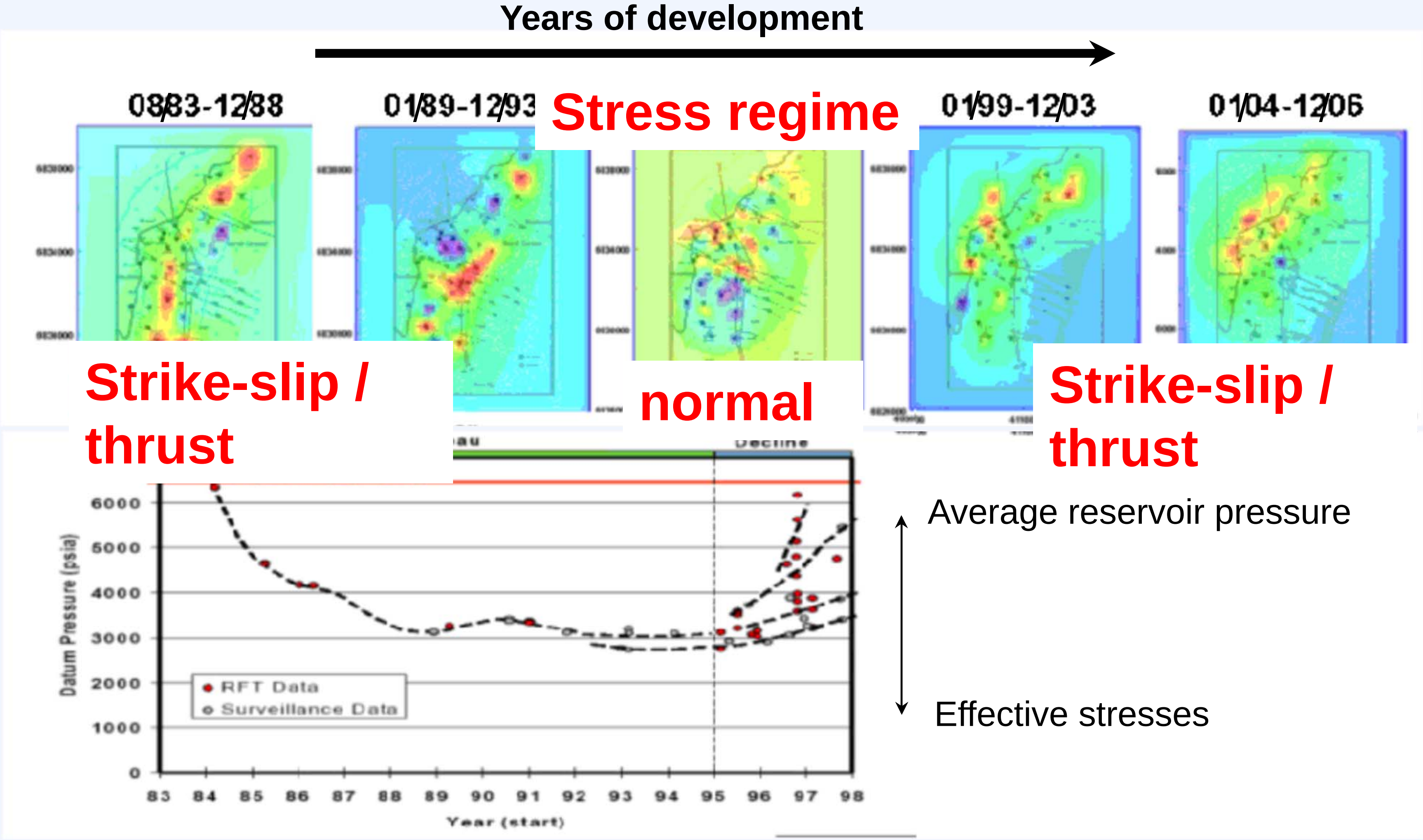
Input to reservoir model history-matching



North Sea ‘unfractured’ field: 1st principal component from rate correlations superimposed on fault trace map

Time-lapse monitoring:

Magnus daily rate data: changes with time in first principal component



Conclusions

- Coupled geomechanics-flow near a critical point is an integral part of reservoir physics affecting commercially important behaviour; in particular it influences flood directionalities
- Inter-well correlations in rate fluctuations are max. in shearing directions; (micro-) fracture interactions explain this as well as being consistent with flood directionalities. Some shear slip also likely.
- Analysis of inter-well correlations in rate fluctuations offers a low cost means of interpreting specific flowpaths between wells, esp. for input to reservoir model history-matching; also allowing time-lapse.
- Modes of deformation can change during field’s life.
- Integration with s-wave data will give most info’.

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