Effect of faults and fractures on oilfield flow rate data: long-range correlations in a complex system

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Schlumberger

Results of ITF (Aberdeen) 'Coffers' project
Data provided by Statoil, sponsored by BP, Shell, Statoil, Conoco-Phillips, Maersk, Total, Hess, BG group, DTI.

References

- **Main, I.G., L. Li, K. Heffer, O. Papasouliotis & T. Leonard (2006). Long-range, critical-point dynamics in oilfield flow rate data, *Geophys. Res. Lett*. 33, L18308, doi:10.1029/2006GL027357.**

- **Heffer, K., X. Zhang, N. Koutsabeloulis, I. Main and L. Li (2007). Identification of activated (therefore potentially conductive) faults and fractures through statistical correlations in production and injection rates and coupled flow-geomechanical modelling, *Society of Petroleum Engineers*, paper no. 107164, 9pp.**

In press

- **Main, I.G., L. Li, K. Heffer, O. Papasouliotis, T. Leonard, N. Koutsebaloulis & X. Zhang (2007). The Satistical reservoir model: Calibrating faults and fractures, and predicting reservoir response to water flood, in Jolley, S. (ed.), *Geol. Soc. Lond., special volume on Complex Reservoirs*.**

- **Zhang, X., N. Koutsebaloulis, K. Heffer, I. Main and L. Li (2007). Analysis of geomechanics and production data for critically-stressed reservoirs – generic characteristics and application to Gullfaks, in Jolley, S. (ed.), *Geol. Soc. Lond., special volume on Complex Reservoirs*.**

Preamble: triggering phenomena

- Earthquake-earthquake
  (Marsan et al, Huc & Main,
  Helmstetter & Sornette, Felzer & Brodsky)
  - static or dynamic?
- Pore pressure-earthquake
  (Segall, Kohl & Megel)
  - poroelasticity and induced seismicity
- Earthquake-pore pressure
  (Doan & Cornet)
  - borehole response
- Pore pressure-pore pressure?
  (Main et al, Heffer et al)
  - flow rate-flow rate

=> Reservoir modelling

Monarch to get a face-lift

KEPPEL FELS of Singapore is to rebuild Diamond Offshore Drilling's ageing Victory-class semi-submersible, Garden Banks (now renamed Ocean Monarch), as a deepwater unit with fifth-generation capabilities.

The $300million reconstruction will result in the rig being able to drill in up to 10,000ft of water using an anchoring system. The revamped rig should be ready for work late-2008.

This is the fourth in a series of fifth-generation Victory-class upgrades that includes the Ocean Baroness, Ocean Rover and Ocean Endeavor. Monarch is currently cold-stacked in the Gulf of Mexico.

Big spender

MEXICAN state operator Pemex plans to invest $30billion in the exploitation of deepwater resources in Mexico's sector of the Gulf of Mexico over the next decade. The first of 10 exploration wells has already been spudded offshore Veracruz on the Noxal prospect in 900m of water. This well alone will cost some $50million and will be followed by the Catai-1 probe.

Pemex is ploughing $10billion this year alone on driving up oil output this year with a massive drilling programme planned. The target is 600 new wells.

Earthquake modelling technique provides reservoir pointers

IN WHAT amounts to smart lateral thinking, researchers at Edinburgh University have used work originally undertaken to aid the understanding of earthquakes to develop models that will help operating companies to optimise their production strategies for mature assets.

Producing oil from mature fields is complex, requiring a detailed understanding of intricate geological structures and their impact on improved recovery techniques such as water injection.

A single platform usually services many wells at different positions in the reservoir. Moreover, a platform may also service numerous wells where water is injected into the rocks to maintain pressure and hence improve recovery from a reservoir.

Modelling reservoir behaviour is used to plan field development and to determine the optimum location of these injector wells. That modelling has to take into account the geological features that dictate whether the injected water will make its way to the relevant location in the reservoir. However, this technique is highly complex and often subject to uncertainty.

As part of a research consortium with companies VIPS and Reservoir Dynamics, the University of Edinburgh has recently developed an approach to reservoir modelling that predicts how the producer wells respond to the injector wells in a way that is different from current reservoir simulation techniques.

In particular, the approach highlights subsurface fluid channels and barriers associated with faults and fractures. The "COFFERS" technique (Calibration Of Faults and Fractures Extracted from Rate Statistics) is based on determining the subset of possible pairs of wells that have a significant effect on each other. The statistical correlations for these selected wells are then used to predict future production rates for a given injection strategy.

The approach uses the principle of developing the simplest model consistent with the data and avoids the problems of noise contamination that has bedevilled similar attempts to produce a reliable "statistical reservoir model". The method has now been proven on two oilfields, one in the North Sea.

Ian Main, Professor of Seismology and Rock Physics at Edinburgh and principal investigator of the consortium, said: "This innovation could have a significant effect on the efficiency of operating oilfields worldwide, especially the more mature fields where optimising recovery is important.

"I had no idea that the theoretical methods we developed to understand earthquake dynamics and interactions would turn out to be so successful in developing this new application."

A new commercial software module to be tested by current sponsors has been developed in collaboration with Earth Decision Sciences.

The COFFERS consortium received funding from eight operating companies and the DTI through the Aberdeen-based technology broker, ITF.

Duncan Anderson, ITF's subsurface technology manager, said: "The COFFERS project has made excellent progress in developing a methodology to model fluid flow in complex reservoirs. It will eventually be possible for operating companies to incorporate the software within their existing workflows to help optimise production strategies."

The COFFERS project will be presented at The Geological Society's Structurally Complex Reservoirs conference, which is being held in London from February 28 until March 2. Indeed, the three-day international conference was inspired by the ITF programme of the same name, of which the COFFERS project was part.

The conference includes leading-edge contributions from industry and academic researchers, specialist providers and practitioners with oil/gas field asset teams. The conference proceedings will be captured in a Geological Society Special Publication.

For more information, contact Duncan Anderson at ITF on d.anderson@oil-itf.com

Outline

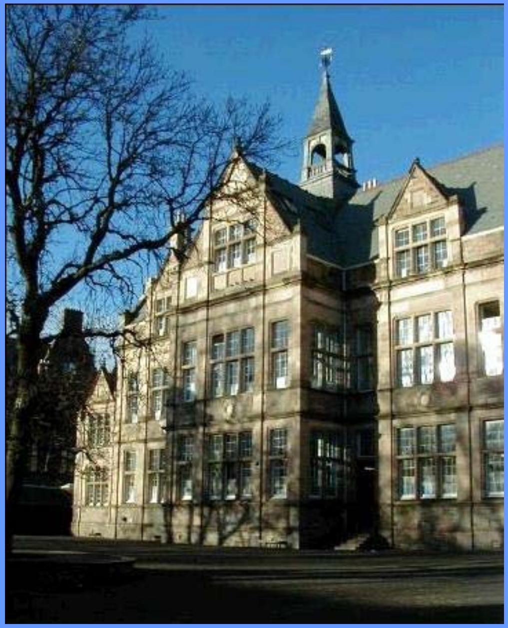
- Background concepts: statistical forecasting, parsimony in model fitting, principal component analysis, geo-mechanics and permeability
- The statistical reservoir model
- Application to the Gullfaks field, North Sea
- Application of a geo-mechanical model to the same field
- Conclusions

Statistical forecasting
Example: Buying a house

$$££ = ??$$

Buying a house: A statistical model

$$££ = w_1 x_1 + \ldots$$



Buying a house: A statistical model

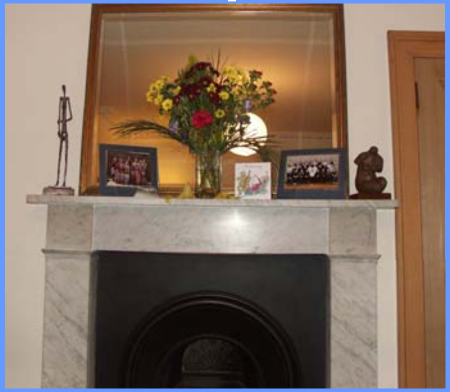
Local School?

$$\pounds\pounds = w_1 x_1 + w_2 x_2 + \ldots$$

Buying a house: A statistical model

Local School? South Facing Garden?

$$££ = w_1 x_1 + w_2 x_2 + \ldots + w_i x_i + w_{i+1} x_{i+1} + ..$$



Buying a house: A statistical model

Local School? South Facing Garden?

$$££ = w_1 x_1 + w_2 x_2 + \ldots + w_i x_i + w_{i+1} x_{i+1} + \ldots w_n x_n$$

Period features?

Buying a house: A statistical model

$w_i, i = 1, n$ Define a set weights

Local School? South Facing Garden?

$$££ = w_1 x_1 + w_2 x_2 + \ldots + w_i x_i + w_{i+1} x_{i+1} + \ldots w_n x_n$$

Period features? Kitchen Sink

SIGNAL NOISE

A History of Parsimony

- ***William of Ockham*: "That which is accomplished by fewer (assumptions) is accomplished in vain with more"**

- ***Carl Friedrich Gauss***

$$\sigma^2 = \sum_{i=1}^{n} [y_i - \hat{\gamma}(x_i)]^2 / (n-p)$$

- ***Hirotsugu Akaike***

$$AIC = n \ln \left\{ \sum_{i=1}^{n} [y_i - \hat{\gamma}(x_i)]^2 / n \right\} - p$$

n = no. of data points
p = no. of parameters

Information vs. goodness of fit

$$y = 1 + x - x^2 : \; \sigma^2 = 1$$

$$BIC = n \ln\left\{ \sum_{i=1}^{n} [y_i - \hat{\gamma}(x_i)]^2 / n \right\} - p[\ln(n/2\pi)]$$

m	3	4	5	6	7	8	9
AIC	0	0.705	0.120	0.078	0.044	0.030	0.023
BIC	0	0.841	0.080	0.046	0.019	0.009	0.005

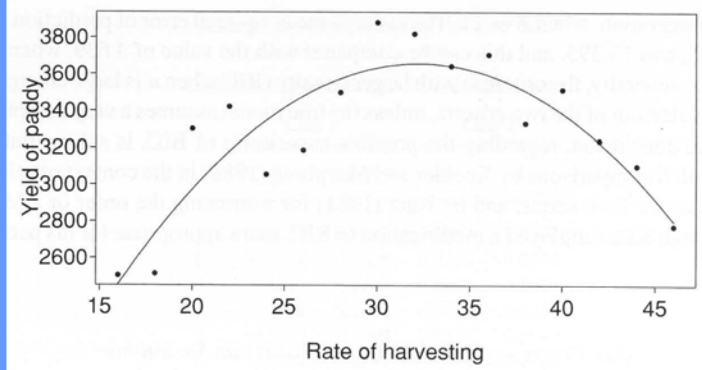


Figure 1.2.8. Fitting a quadratic regression curve.

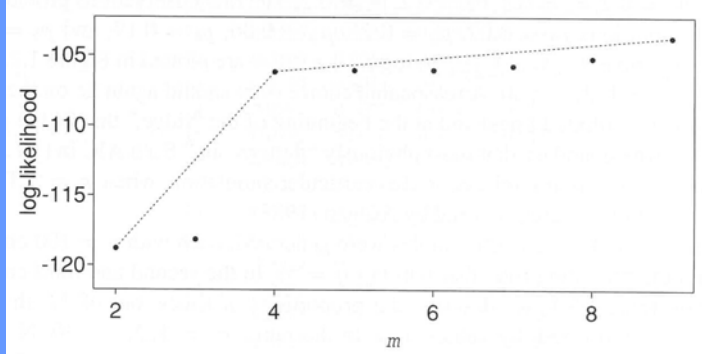


Figure 1.2.9. Log-likelihood plot for polynomial regression.

Principal component analysis
Example: stress rotation

$$\begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{bmatrix} = R^T(\theta,\phi) \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix} R(\theta,\phi)$$

$$\sigma_1 \geq \sigma_2 \geq \sigma_3$$

Second Example: mineral prospecting

Table *1.1. The raw data matrix for the lead–zinc prospecting problem*

			Causes	Mg in calcite	Fe in sphalerite	Na in muscovite	Sulfide	Crystal size of carbonates	Spacing of cleavage	Elongation of ooliths	Tightness of folds	Vein material per m^2	Fractures per m^2
				Geological properties									
			T	0.95	0.75	0.75	0.33	−0.20	0.05	0.20	0.10	0.00	0.05
			D	0.00	0.10	0.20	0.33	0.60	0.95	0.70	0.85	0.10	0.25
			P	0.05	0.15	0.05	0.34	0.60	0.00	0.10	0.05	0.90	0.70
Locality	*T*	*D*	*P*	Data matrix									
1	121	21	46	117.25	99.75	97.25	62.50	16.00	26.00	43.50	32.25	43.50	43.50
2	96	35	42	93.30	81.80	81.10	57.51	27.00	38.05	47.90	41.45	41.30	42.95
3	78	54	49	76.55	71.25	71.75	60.22	46.20	55.20	58.30	56.15	49.50	51.70
4	63	51	49	62.30	59.70	59.90	54.28	47.40	51.60	53.20	52.10	49.20	50.20
5	42	44	44	42.10	42.50	42.50	43.34	44.40	43.90	43.60	43.80	44.00	43.90
6	39	26	54	39.75	39.95	37.15	39.81	40.20	26.65	31.40	28.70	51.20	46.25
7	52	36	52	52.00	50.40	48.80	46.72	42.40	36.80	40.80	38.40	50.40	48.00
8	67	46	54	66.35	62.95	62.15	55.65	46.60	47.05	51.00	48.50	53.20	52.65
9	90	37	51	88.05	78.85	77.45	59.25	34.80	39.65	49.00	43.00	49.60	49.45
10	108	27	61	105.65	92.85	89.45	65.29	31.20	31.05	46.60	36.80	57.60	54.85
11	112	33	59	109.35	96.15	93.55	67.91	32.80	36.95	51.40	42.20	56.40	55.15
12	91	38	59	89.40	80.90	78.80	62.63	40.00	40.65	50.70	44.35	56.90	55.35
13	76	39	54	74.90	69.00	67.50	56.31	40.60	40.85	47.90	43.45	52.50	51.35
14	63	30	51	62.40	57.90	55.80	48.03	36.00	31.65	38.70	34.35	48.90	46.35
15	43	19	55	43.60	42.40	38.80	39.16	35.80	20.20	27.40	23.20	51.40	45.40
16	68	16	42	66.70	58.90	56.30	42.00	21.20	18.60	29.00	22.50	39.40	36.80
17	77	27	41	75.20	66.60	65.20	48.26	25.40	29.50	38.40	32.70	39.60	39.30
18	93	37	43	90.50	79.90	79.30	57.52	29.40	39.80	48.80	42.90	42.40	44.00
19	102	47	48	99.30	88.40	88.30	65.49	36.60	49.75	58.10	52.55	47.90	50.45
20	120	36	46	116.30	100.50	99.50	67.12	25.20	40.20	53.80	44.90	45.00	47.20

Map of first three principal components

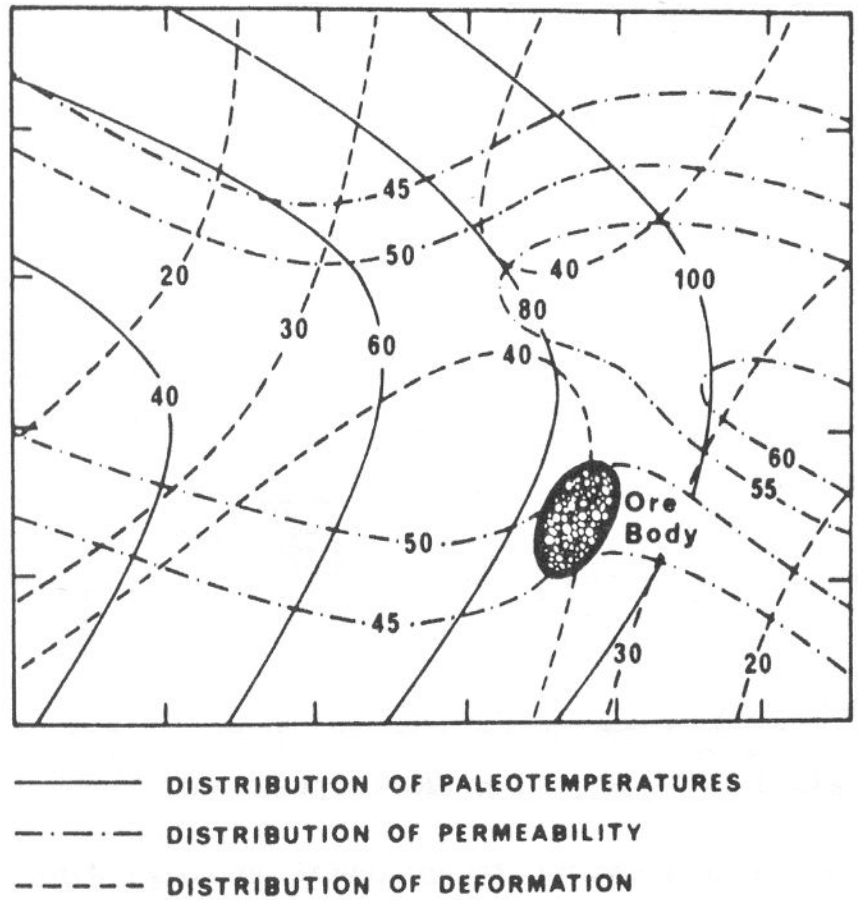
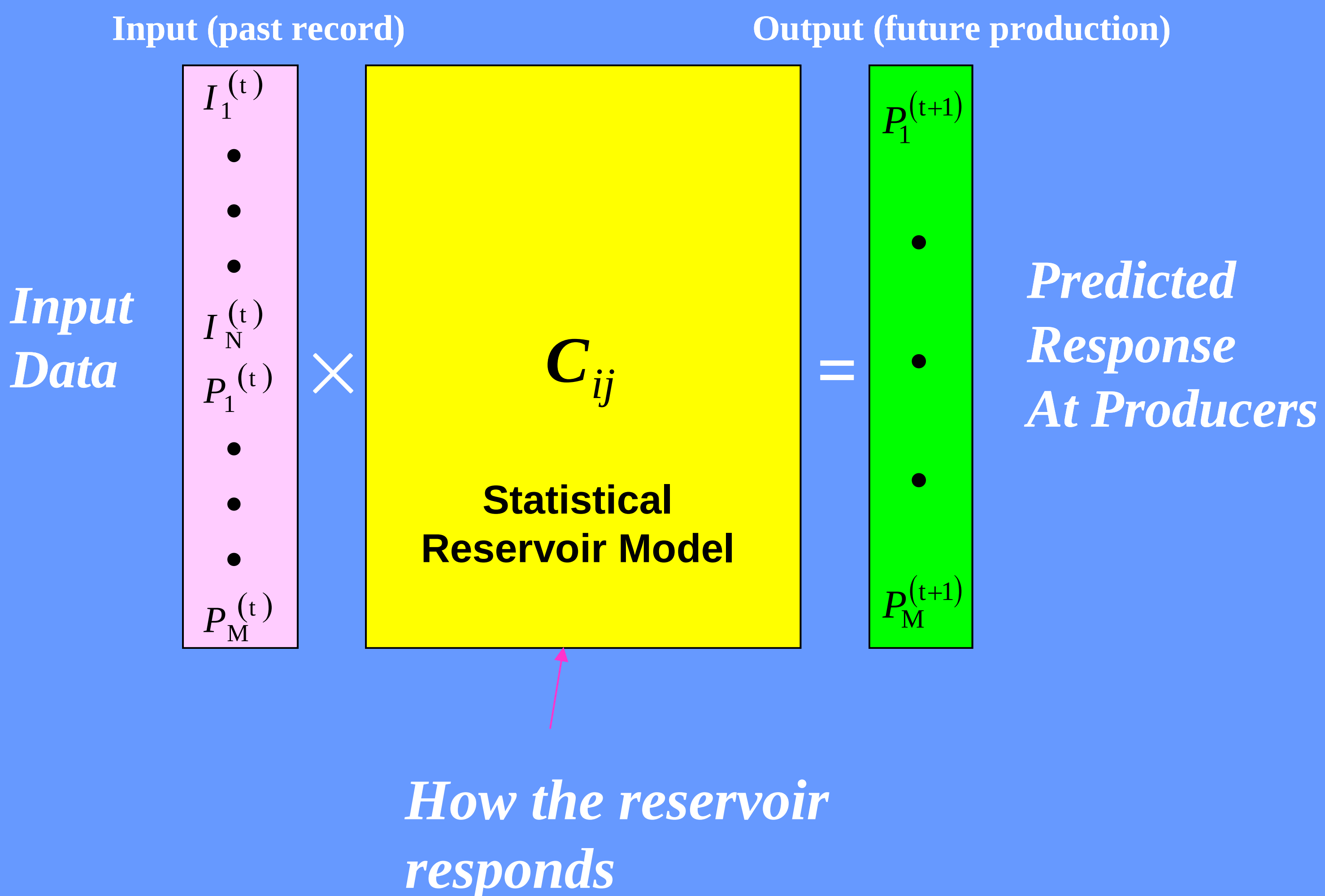
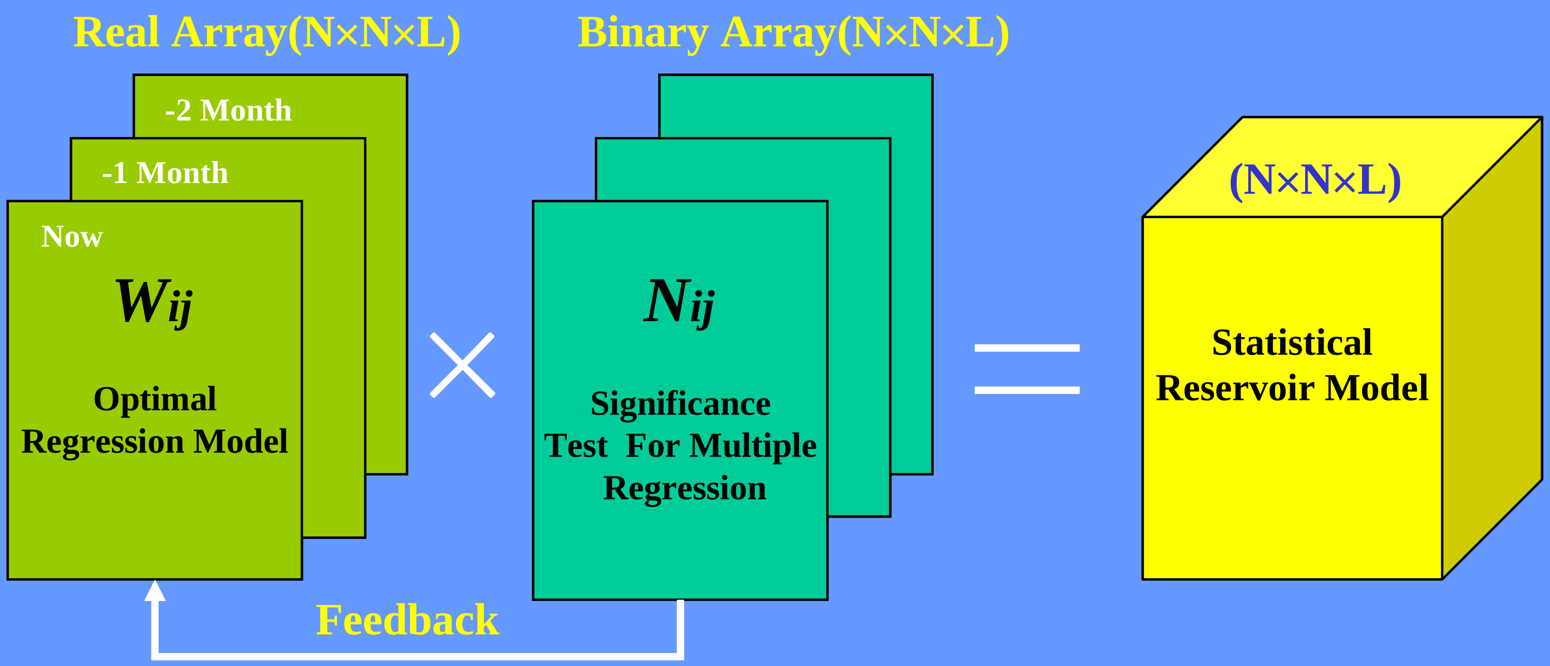


Figure 1.2. Distribution of controls imposed at the locations of the samples.

The statistical Reservoir Model

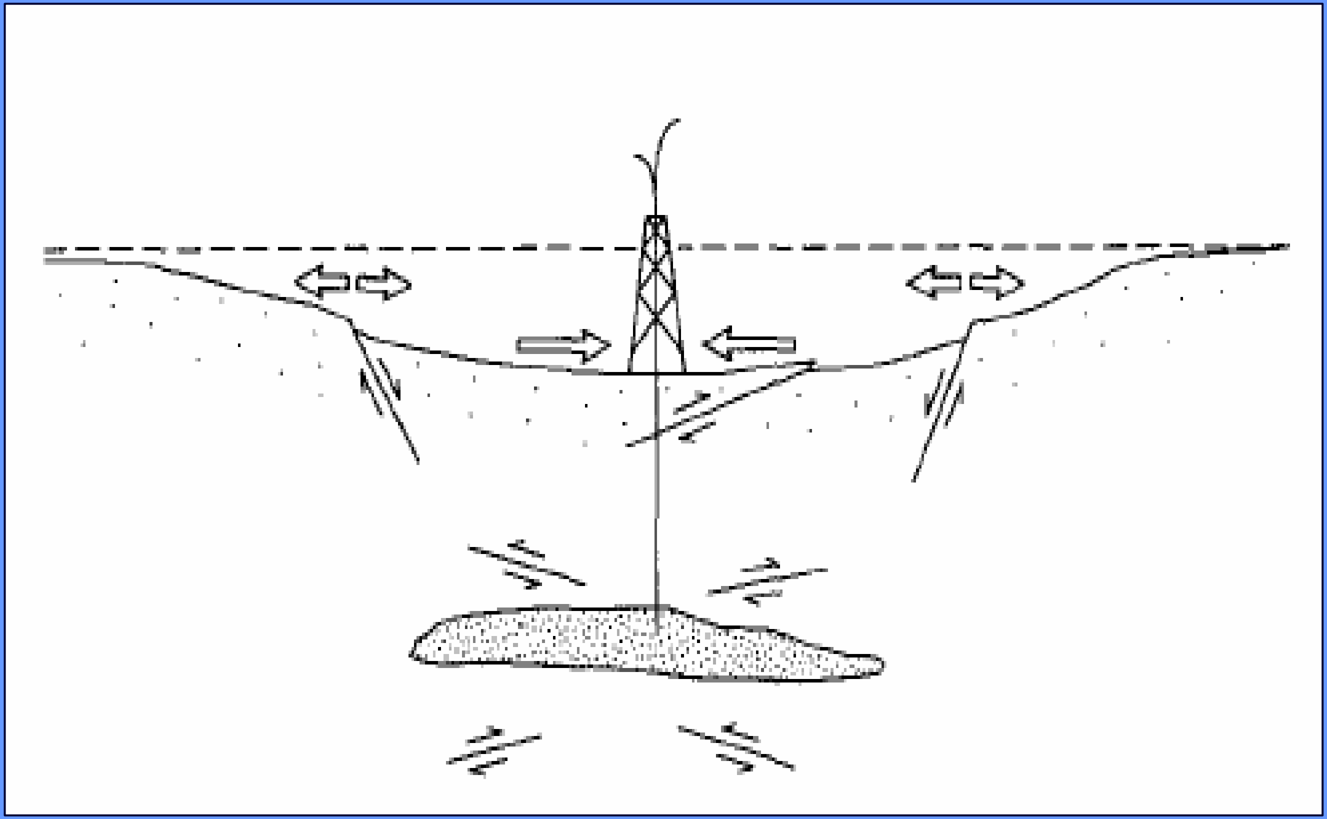


Separating signal from noise: a parsimonious model



UK patent application 0524134.4 filed 26/11/2005

Geo-mechanical model: long-range poro-elasticity

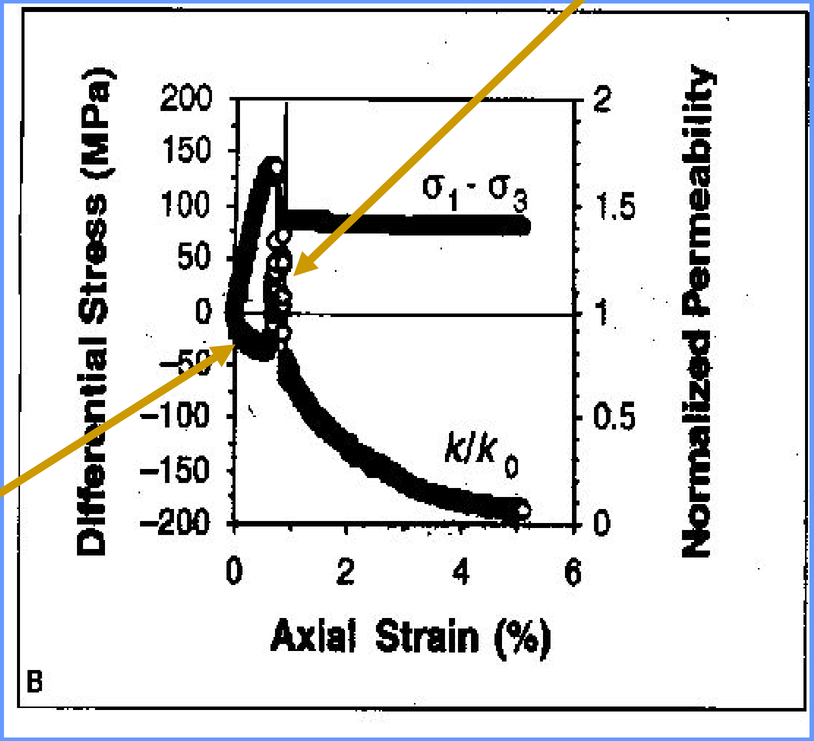


Deformation and faulting associated with fluid extraction (*Segall*, 1989)

Geo-mechanical model: Permeability response to deformation

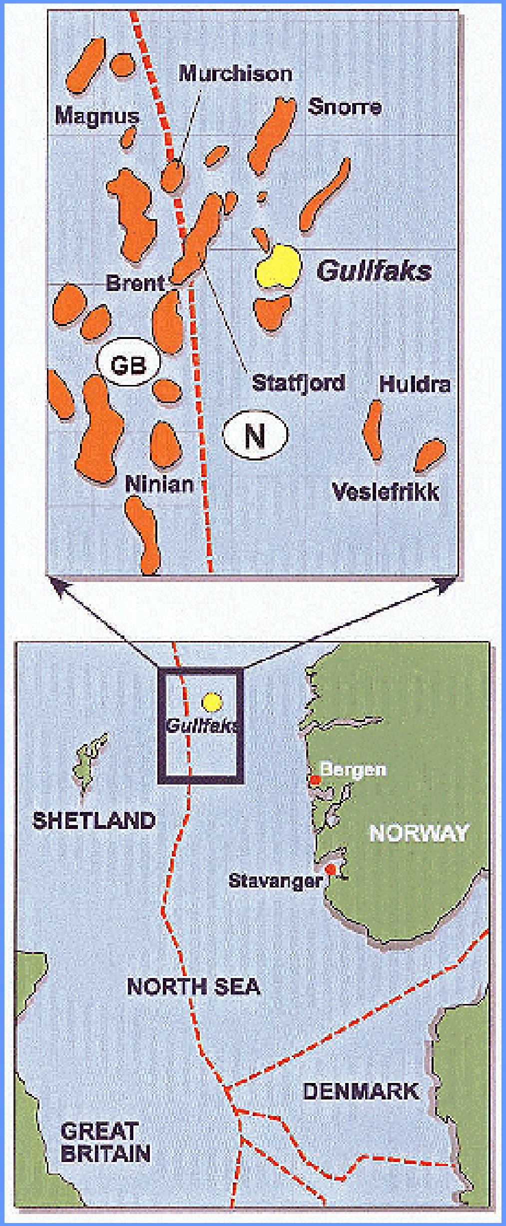
Non-linear, near critical

Linear

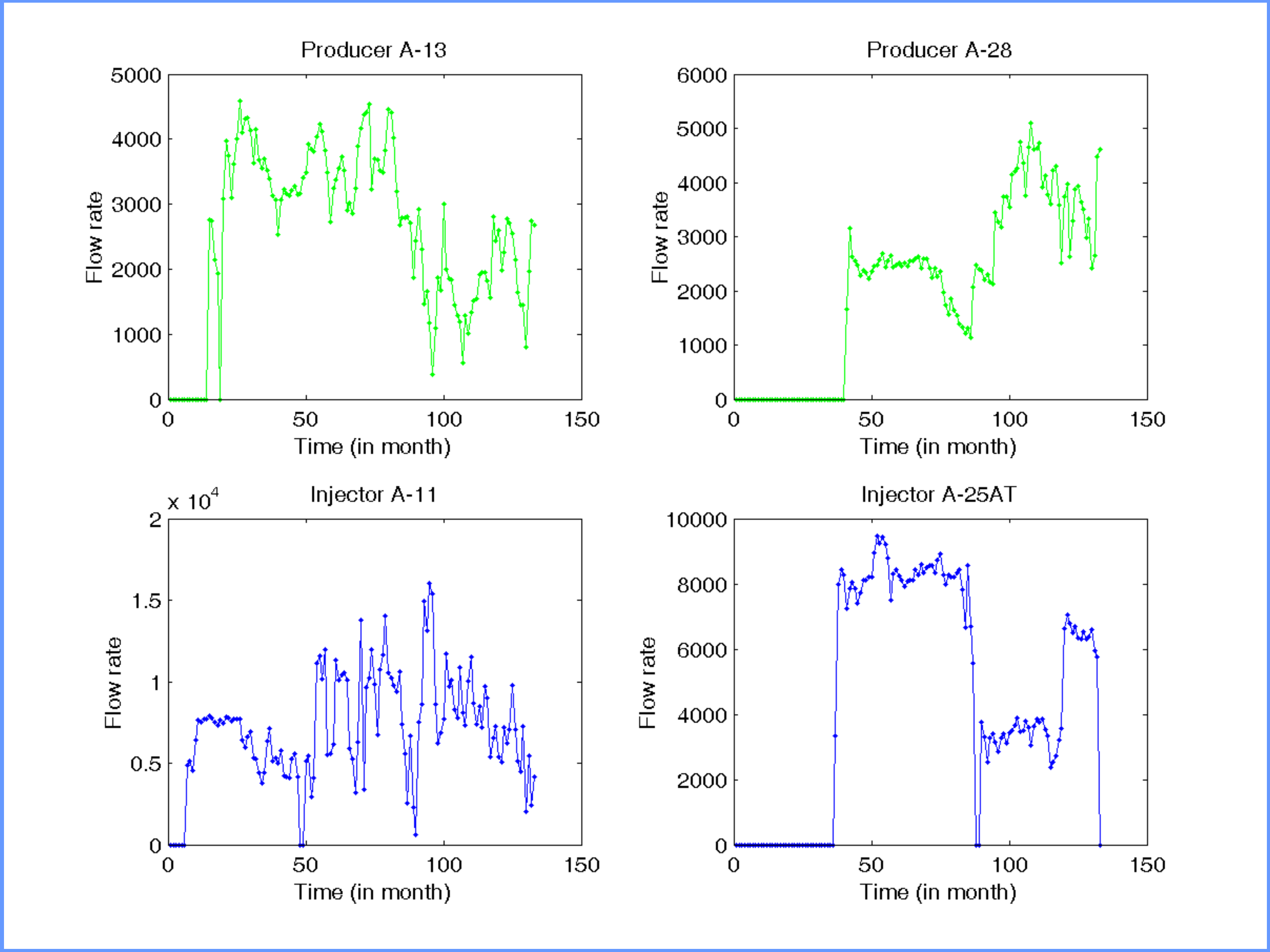


Test case: The Gullfaks field (after *Arild Hesjedal*)

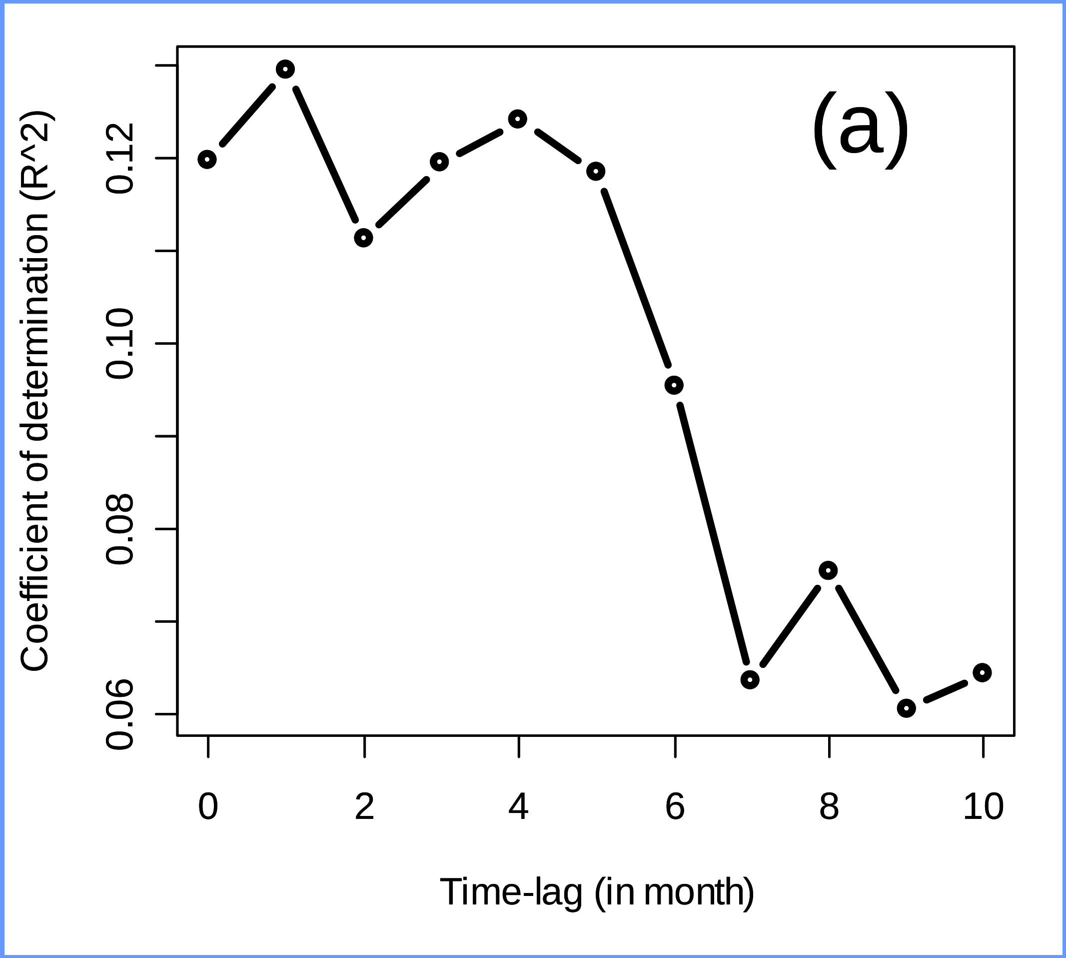
- Complex, faulted reservoir
- In block 34/10 in the northern part of the Norwegian North Sea.
- Total of 133 months data 1986-1997
- 106 platform wells (79 producers +27 injectors >24 months) used
- Data provided free for academic use



Time series for flow rate

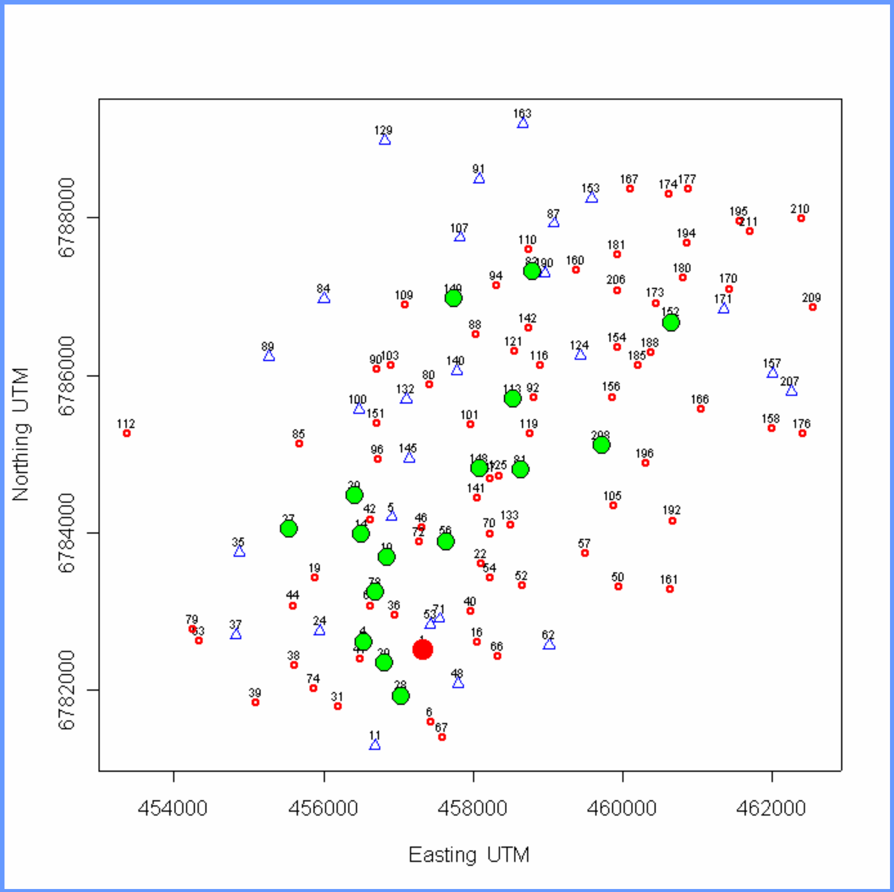


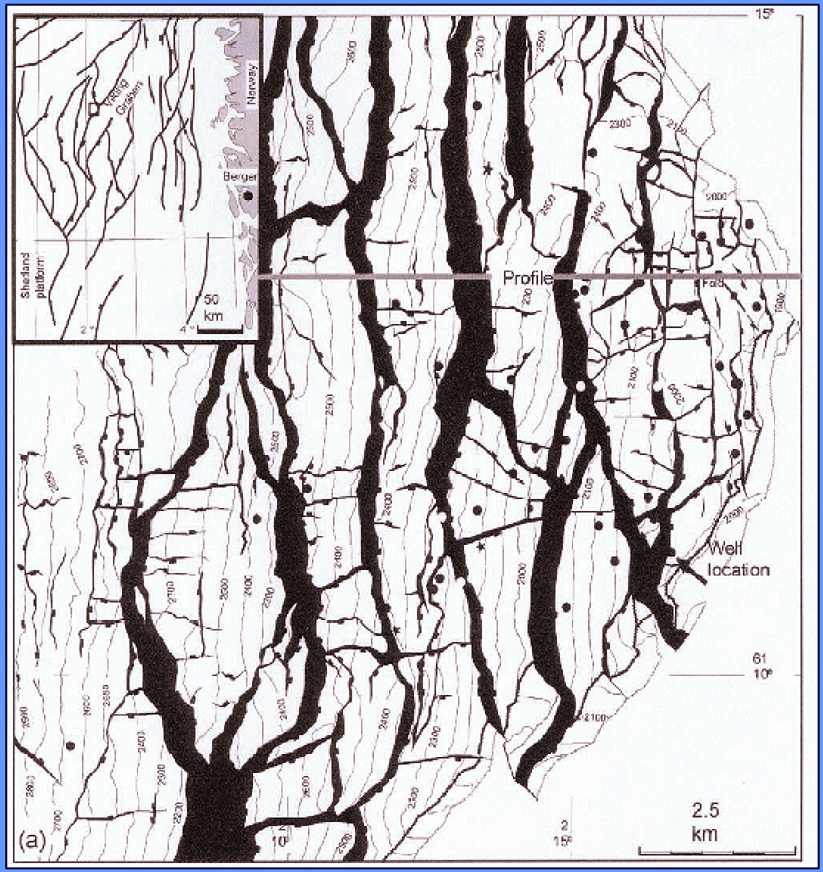
Cross-correlation function



‘Direct’ and time-delayed effects seen over a few months

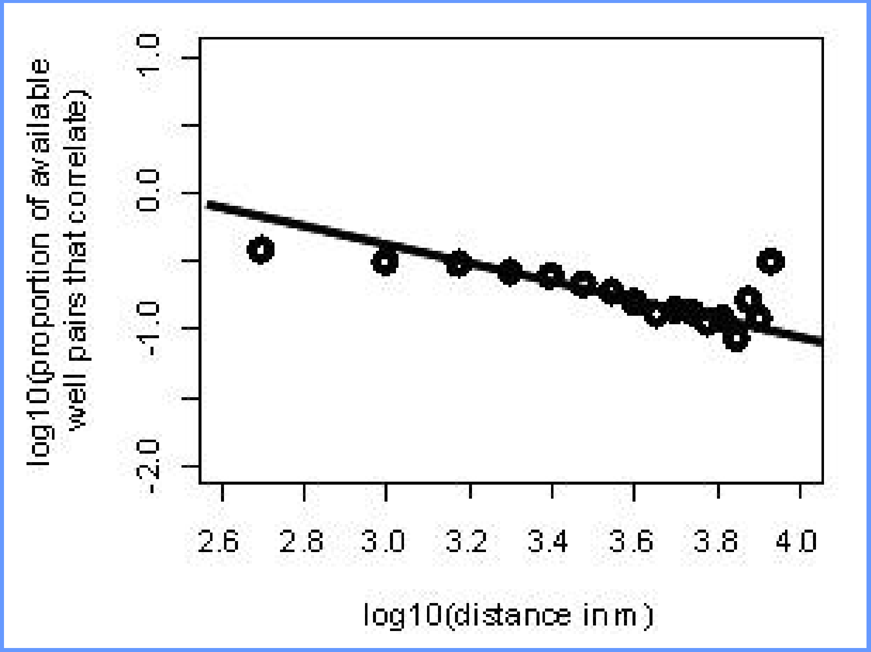
Significantly correlated wells



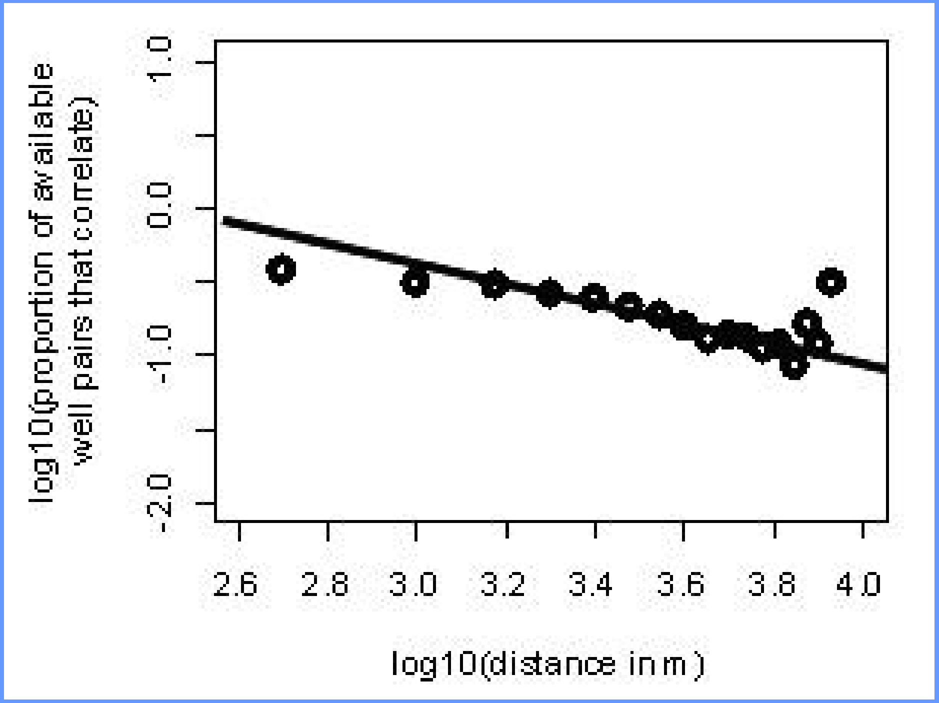


Fault map of the Gullfaks Field (*Fossen et al.*, 1998).

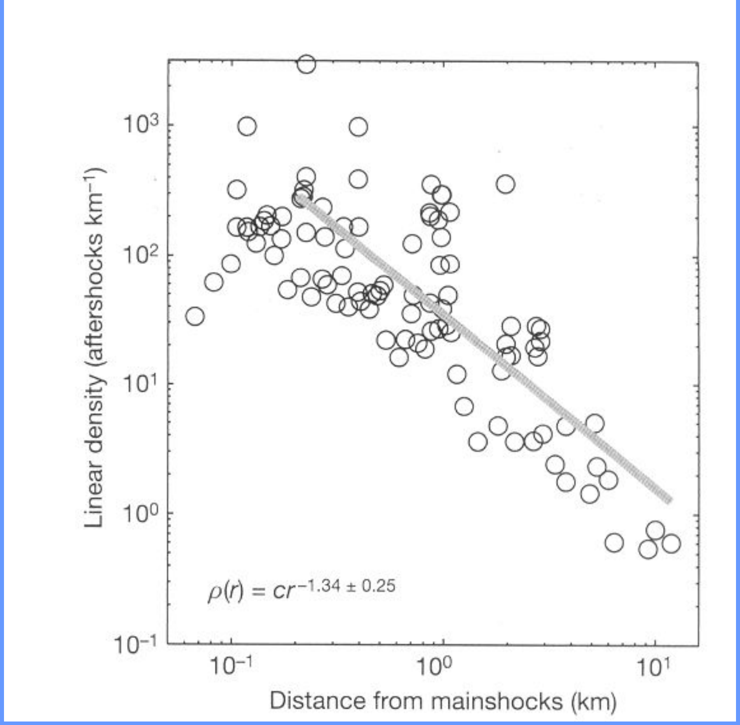
Correlation function for significantly correlated wells



Correlation function for significantly correlated wells

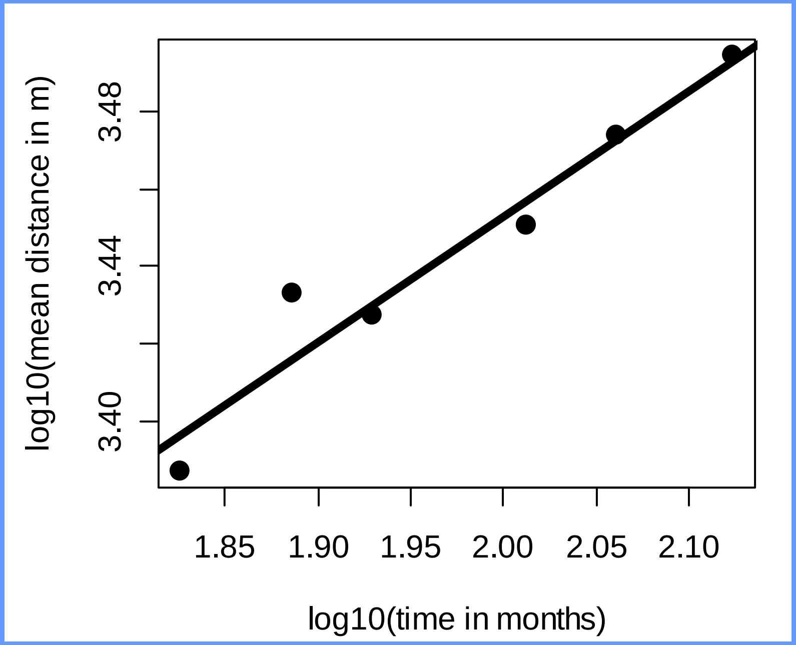


Flow rate correlations



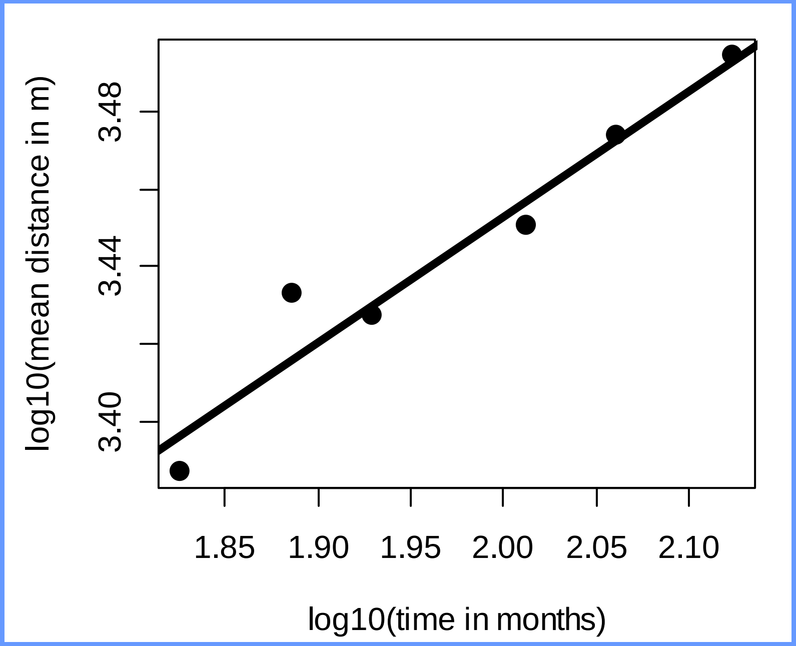
Earthquake aftershocks
(Felzer & Brodsky, 2006)

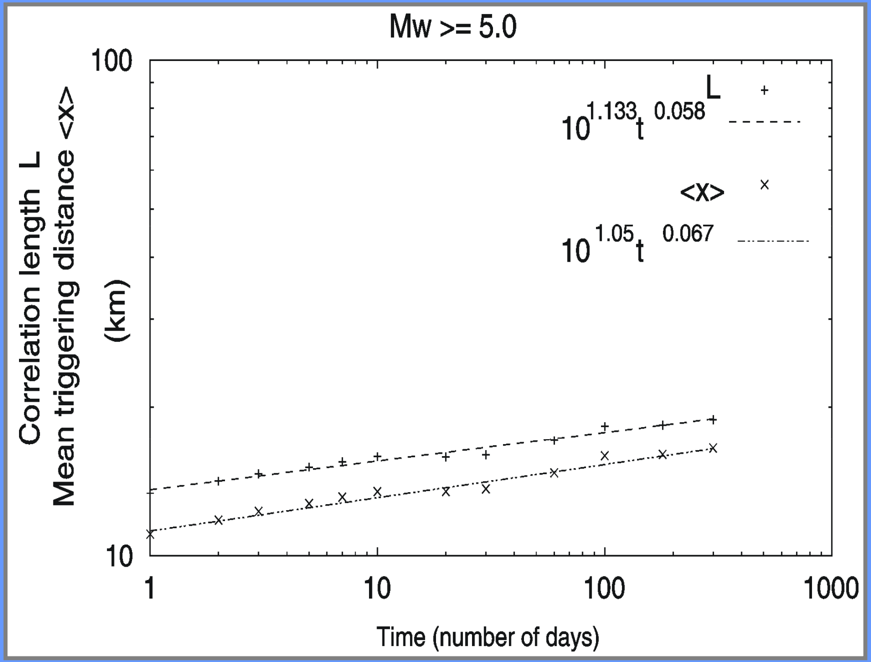
Anomalous (slow) diffusion



<x>~$t^{0.3}$ for significantly correlated well pairs

Anomalous (slow) diffusion

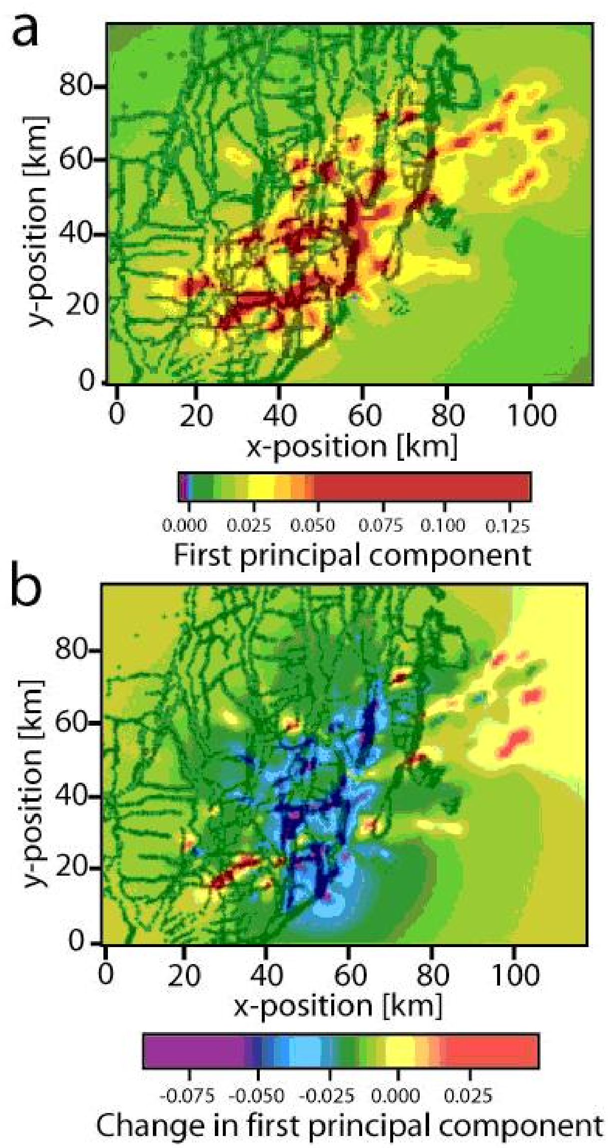




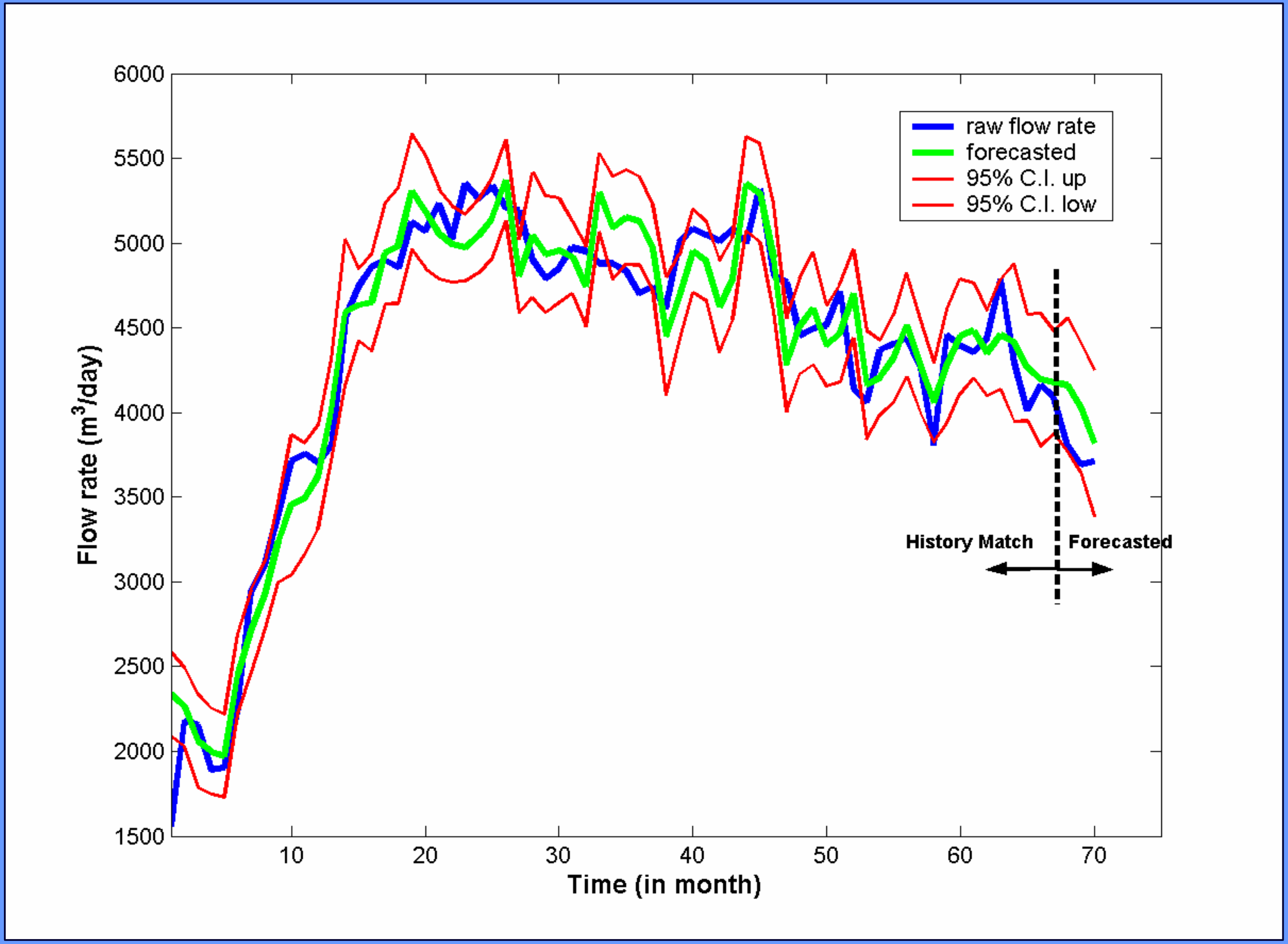
$<x> \sim t^{0.3}$ for significantly correlated well pairs

$<x> \sim t^{0.07}$ for earthquakes (Mw>=5.0) (Huc & Main, 2003)

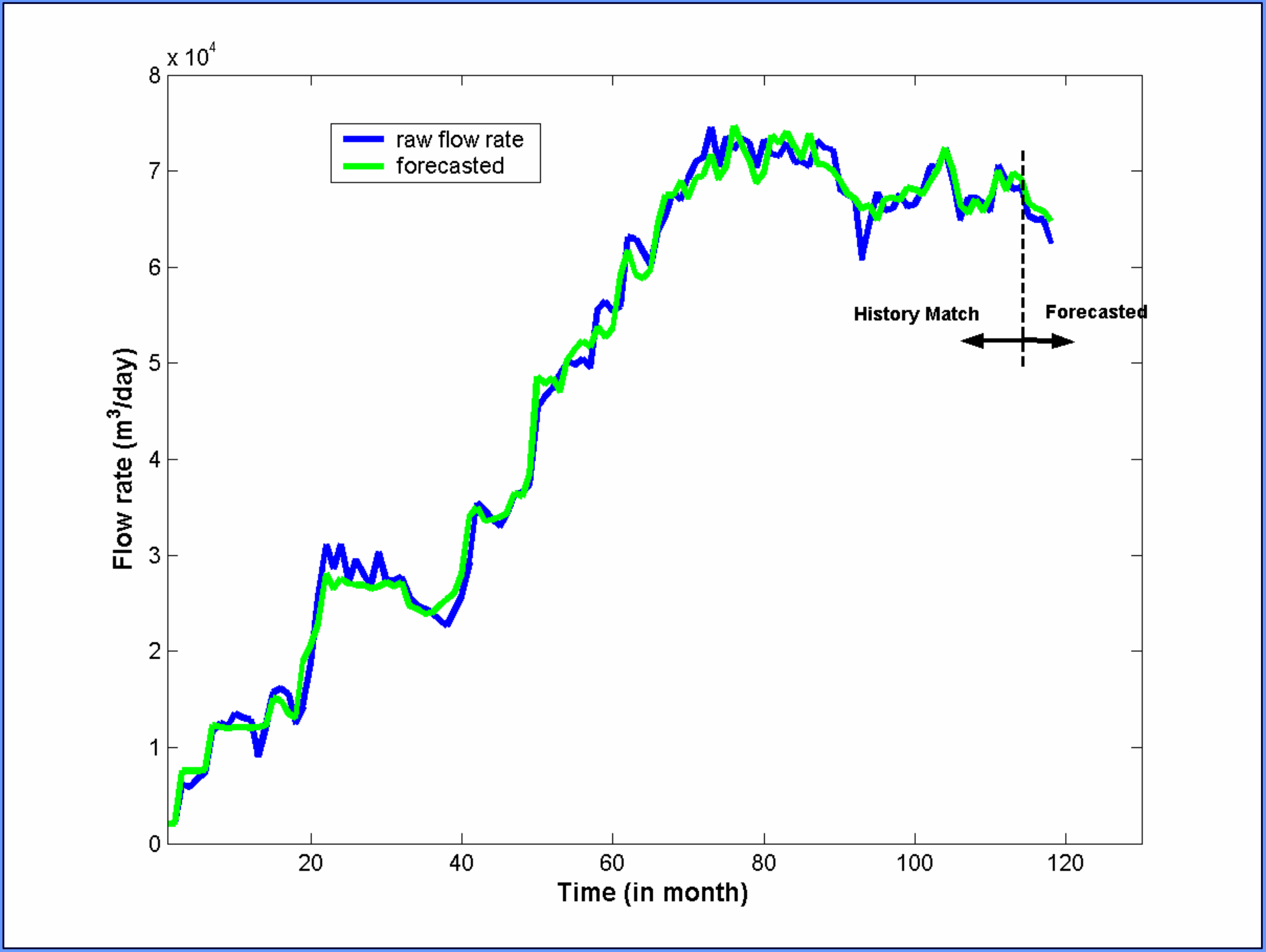
Principal component analysis



Predictive trial for a single well

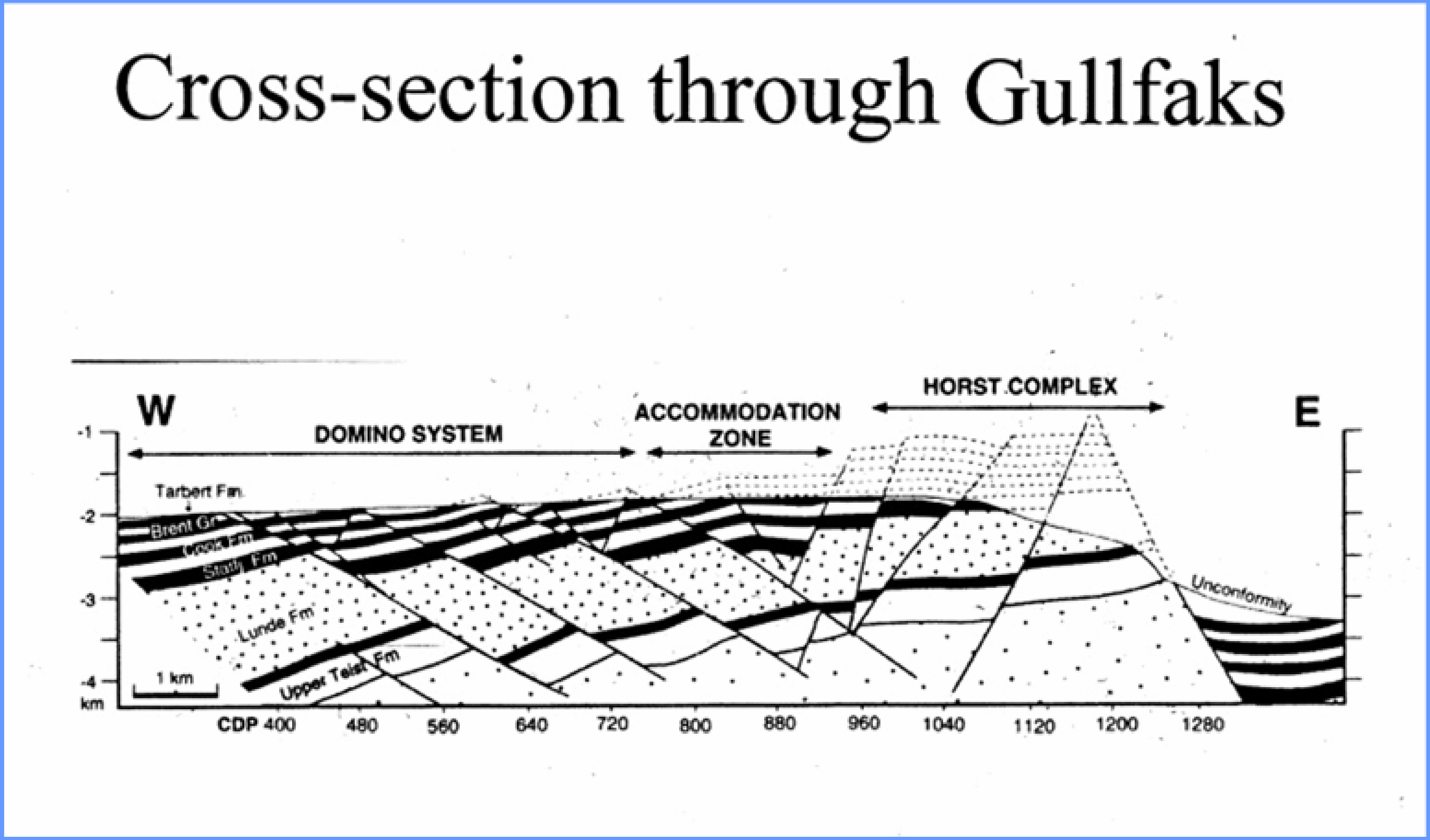


Predictive trial for a group of wells



Note good statistical averaging

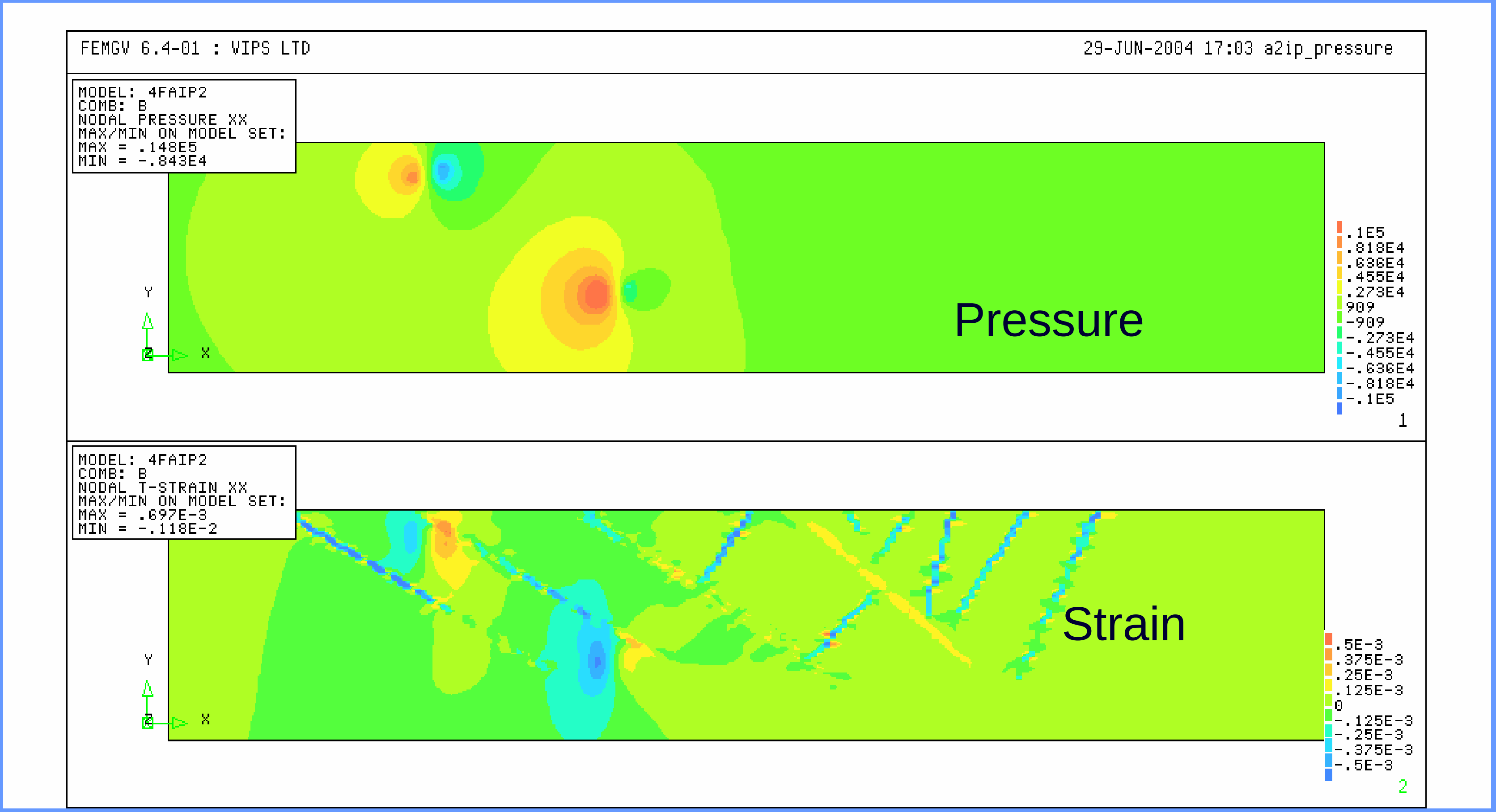
Geo-mechanical model: Reservoir architecture



Fossen & Hesthammer (1998) 2D cross section

Geo-mechanical simulation

(2D model in cross section)



Pressure change and volumetric strain: critical case

Geo-mechanical simulation

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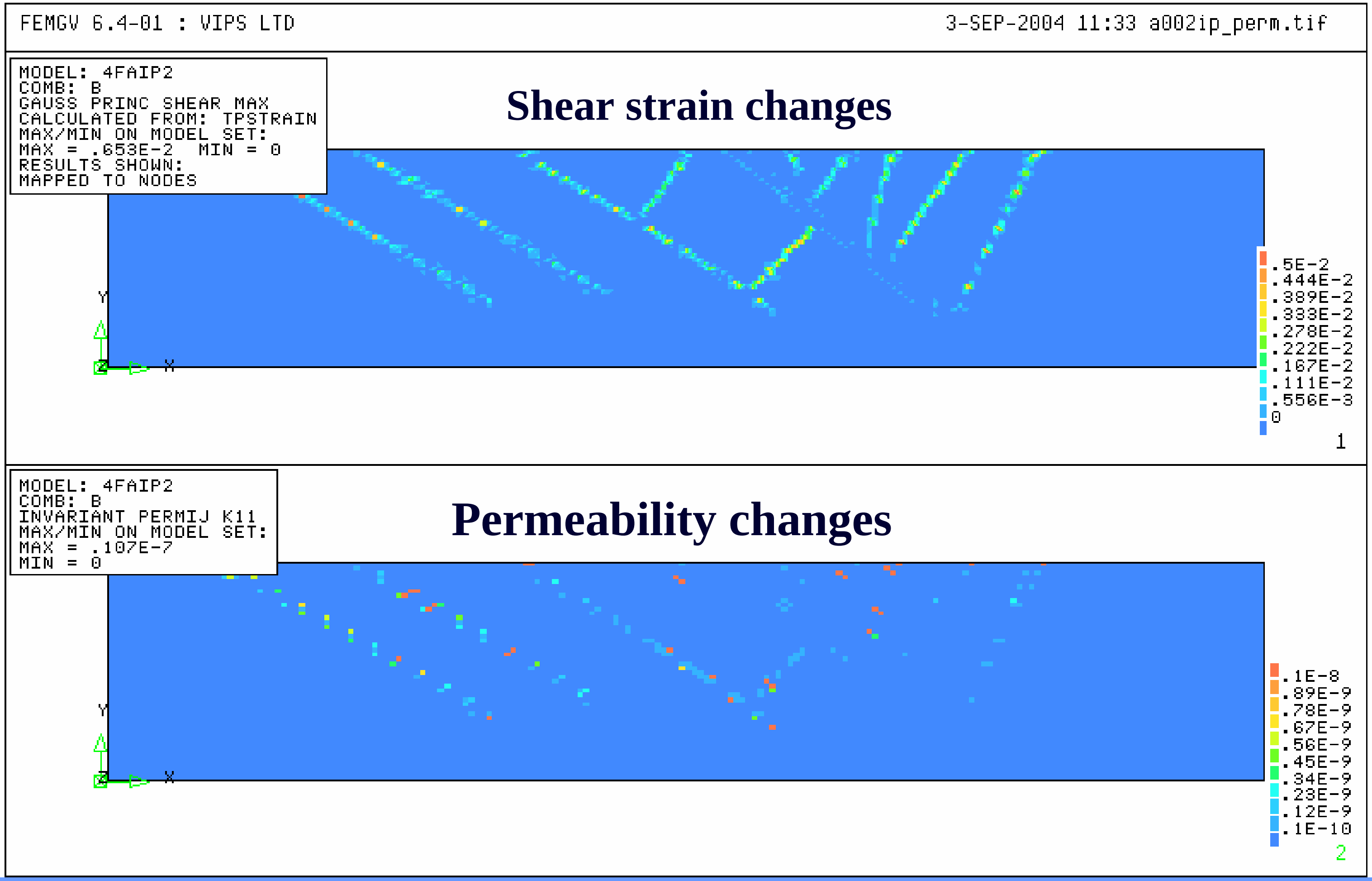
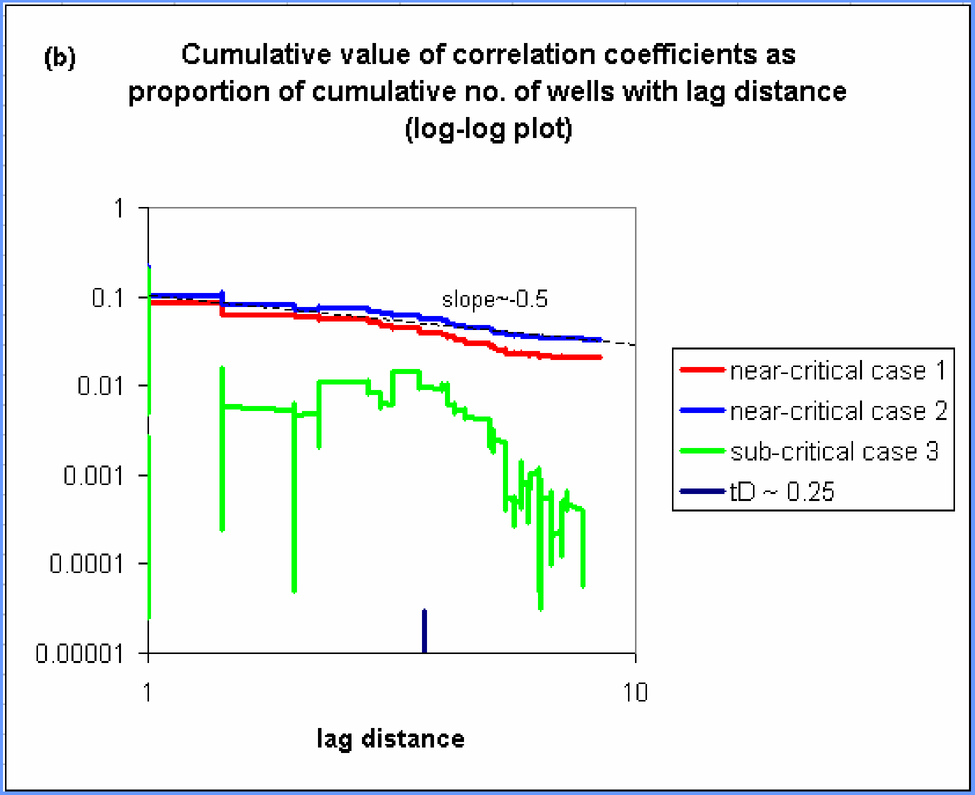
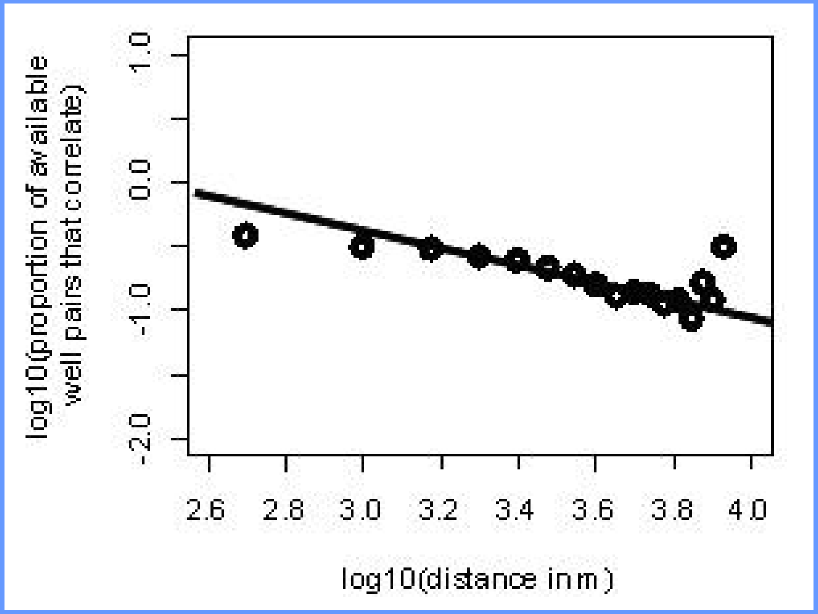


Geo-mechanical simulation

(2D model in plan view for a synthetic regular grid of wells)





c.f. data from Gullfaks

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Conclusion

- Oilfield flow rate correlations behave very similarly to earthquake-earthquake triggering
- The results agree with deterministic geo-mechanical simulations *iff* the system is critical
- The first principal component agrees with fault architecture
- Good short-term predictability
- Many potential applications

Next steps…

- Further field trials (DTI 'RESURGE' project)
  - more data welcome
- Calibration and interpretation of principal components
- Compare with induced seismicity response (independent validation of geo-mechanical simulations)
- Apply to earthquake-earthquake triggering (EU 'TRIGS' network)