Identification Of Activated (Therefore Potentially Conductive) Faults And Fractures Through Statistical Correlations In Production And Injection Rates And Coupled Flow-Geomechanical Modelling

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Abstract

Long-range, stress-related and fault-related characteristics of correlations in fluctuations in flow-rates are explained conceptually in the context of the lithosphere’s near-critical mechanical state and a strong feedback between deformation and local permeability. A more sophisticated statistical model, devised to extract a parsimonious set of flow-rate correlations, has shown similar characteristics. Coupled geomechanical-flow modeling was able to reproduce those characteristics for a generic pattern waterflood perturbed with random noise, but only when loaded to a near-critical state, hence providing strong support for the conceptual model. Coupled modeling of a cross-section representative of the Gullfaks field also demonstrated long-range influences. The matrix of empirical correlations between all well-pairs for a field can be decomposed in various ways. The principal components of the matrix, when interpolated with appropriate spatial correlation functions, have indicated the importance of particular faults in the rate fluctuation history; it is inferred that those faults are mechanically active during the development, and thus are potentially conductive features.

Introduction

It is usually assumed that geomechanical modelling coupled with reservoir simulation is only required in a minor subset of reservoirs that are termed ‘stress-sensitive’. This subset is sometimes recognized a posteriori; i.e. during the course of field development, often through a general severe decline in permeability levels with depleting pressure; or perhaps a priori in the case of weak reservoir rocks where compaction drive is considered important to recovery (e.g. unconsolidated sands or weak chalks). Rarely outside such bounds is geomechanical modelling deemed necessary for reliable, unbiased reservoir performance predictions. However, some past analyses of preferred directions of flooding\textsuperscript{1,2}, and of the correlations in rate fluctuations\textsuperscript{3} have suggested that geomechanics may be playing a commercially significant role in many secondary and tertiary floods, if not other development schemes. Key to the interpretation of this field data are the following concepts, which may be novel to many reservoir engineers or geoscientists:

1. Much of the lithosphere is in a near-critical state\textsuperscript{4,5}. This means that there are percolating paths of faults, fractures and incipient fractures that are near mechanical failure in the prevailing stress states. This concept is supported by direct measurements of stress state\textsuperscript{6,7}, observations of (micro-)seismicity induced by oilfield development\textsuperscript{8}, shear-wave splitting observed in most types of rock in the crust\textsuperscript{9}, and the observations of so-called ‘1/f’ scaling of properties in well-logs\textsuperscript{10}.

   These observations are themselves underpinned by theoretical explanations of the evolution of the earth’s lithosphere into a near-critical state. Such models include ‘self-organized criticality’ (SOC)\textsuperscript{11-15}, or ‘self-organized sub-criticality’\textsuperscript{16,19}, or in the sense of a spinodal critical point\textsuperscript{20}. Whilst there is still ongoing discussion as to which of these models best fits lithospheric deformation, common characteristics of these theories, also observed in the real behaviour of rock, are:

   - Strong susceptibility to small perturbation (metastability)
   - Responses often at a distance from perturbing load (long-range correlation)
   - Percolating paths of incipient failure (localization), oriented in association with the modern-day stress state.

Note that in addition to individual points on faults or fractures being critically-stressed, the term ‘critical’ applies more importantly to the state of the whole system, which implies that it is on the border between being rigid and weak. It is pertinent to read Bak’s\textsuperscript{14} interpretation of how an hypothetical observer (whom we might take to be a reservoir engineer!) within a system in a state of SOC might (mis-) construe events: explanations of local events in terms of traditional understanding of mechanisms miss.
the long-range correlations and possibility of extreme or catastrophic events characteristic of SOC.

There is currently insufficient precision in both theory and field stress measurements to be able to quantify the nearness of ‘near-criticality’. Also, even in a state of SOC, the critically-stressed pathways comprise but a minor portion of the rock volume, surrounded by extensive sub-critical regions. On the other hand, a perturbation that itself influences a spatially extensive region, say with fluid pressure change, is more likely to encompass some critically-stressed set of points within it. Additionally one should note that hydrocarbon reservoirs, by their very nature, are predominantly located in salient structures, which are likely to provide foci for local pathways of contemporary failure; those pathways can play important rôles in the hydro-mechanical behaviours of reservoirs as they are perturbed by development.

2. Related to the above, bulk permeabilities of rock can change with the changing stresses that are induced by the development of an hydrocarbon reservoir. Permeability changes accompany either dilatation or compression of fractures or faults or new fractures in previously intact rock. It will be suggested later in this paper that shear failure appears to be a prime factor in controlling such changes. For fractures or faults in strong rocks, usually those with lower porosity, dilatation can occur as the roughnesses of opposing walls of ride over each other during (incipient) shear. Conductivity of faults can decrease during shear if the fault fill is ductile in nature or if normal stresses on the fault are high relative to the strength of the asperities. Laboratory experiments have indicated that the permeability of high porosity, weaker, sands tends to decrease, sometimes dramatically, as they yield cataclastically at high mean stresses; permeability decreases occur even as brittle failure occurs at lower mean stresses despite associated dilatancy. However, such experiments have reported a short-lived increase in permeability at the brittle failure point itself. One recent thermodynamic model of damage (microcrack development) and porosity evolution in deforming material predicts such an increase in permeability. Additionally, most such experiments have been run with increasing average stresses; it is arguably more probable that low and decreasing stress states will also cause conductive fractures as they fail in brittle shear. The probability of permeability increase on failure is greater if the sands have been initially compressed beyond their ductile failure envelope before then being de-stressed (when the state of the sands is termed ‘over-consolidated’), as will occur with increasing pore pressures and decreasing temperatures associated with injection. Nygård et al. demonstrated permeability increase in the laboratory for brittle failure of over-consolidated mudrocks. Du Bernard et al. provided field evidence of the existence of dilation bands, of probably high permeability, in high porosity sands, created under low effective stress conditions. Given near-criticality, much of the deformation induced by oilfield development in a reservoir and its surroundings is likely to be focussed on reactivation of parts of the pre-existing faulting structure. However, although some permeability changes will be controlled by the fault properties, the strain changes associated with new shearing on those faults will be distributed over extensive lobes around each end of the slip zone (figure 1), where permeability changes will depend upon the local properties and deformation.

So, permeability changes can be a complex function of initial stress state, stress path during deformation, pre-existing structural configuration, history of the deformation and properties of the fault fill or gouge and of the intact rock. Relative permeabilities at various scales might also be changing, although little has been published on this issue.

Statistical analyses of well rate fluctuations
Rate histories (generally month-by-month) at individual wells in an oilfield can be treated as a set of time series, between which various correlations can be calculated. The fluctuations in rates are caused either by changes to well or to topside conditions, or to interfering signals passing through the reservoir. It is assumed that the former will have little correlation structure (without abandoning caution against such), whilst the latter will be more systematic. The objective of statistical analyses is to extract the reservoir-related signals from other noise, and to infer physical mechanisms from the results. It is conventional to assume that intra-reservoir signals are hydraulic in nature, dependent solely on Darcy flow within the spatial distribution of permeability: we aim to demonstrate here that at least part of the signals are, in general, due to geomechanical processes.

Previous analyses. Heffer et al. used the standard, non-parametric technique of Spearman rank correlation to analyse correlations with zero lag between the fluctuating production and injection rates at well pairs over several fields. In line with the concepts discussed in the introduction they found that:

a) the orientations of the strongest correlations occurred for well-pairs that are aligned sub-parallel to the local direction of the maximum horizontal principal stress axis (S_H). Figure 2 shows the orientational distributions of t-statistic associated with correlation coefficient from several field areas, each relative to the local orientation of S_H, which is rotated to be up and down the figure. One particular field case is shown in figure 3, for the Gullfaks field in the Norwegian North Sea. In this, various cut-offs in significance level of correlation have been applied. For the higher levels of significance (lower probabilities of true correlation), there was a confusing orientational distribution of correlation coefficients; however, for the lower significance levels (most probable correlations), the orientational distributions fell into two peaks, which were 30 degrees either side of the direction of S_H indicated by measurements in a nearby field. This pattern is consistent with the
directions of shear in a strike-slip stress regime. The Gullfaks field is set in a region of the North Viking graben of the North Sea where the modern-day stress regime has been interpreted as intermediate between strike-slip and thrust. Many of the strongest correlations were between wells separated by large distances. Figure 4 shows the variation with lag-distance of the proportion of available well-pairs that are correlated (by Spearman rank analysis) at given significance levels for the Gullfaks field. Even at the highest significance level, there is little decay with distance.

b) There was also an association between some of the strongest correlations and fault trends

In contrast, other workers have determined inter-well connectivities with this technique assuming local Darcian flow.

**Statistical Reservoir Model (SRM).** Main et al. have devised the more sophisticated concept of the Statistical Reservoir Model, which is briefly described as follows. The response of the reservoir at a particular well is modelled using linear multivariate regression on the rates at other wells at various lag-times, but, crucially, in a sequence that is optimised according to two different criteria. First, the well pairs that are significantly correlated at different lag times are identified using a Bayesian Information Criterion. This removes well pairs that do not significantly contribute information. Second, Bayesian Dynamic Linear Modelling is used to eliminate a lower number of pairs whose optimal regression slope is not significantly different from zero. These two steps result in a parsimonious model in which typically only 5-25% of the wells in a field are determined as significantly influencing the rate history at each subject well.

The SRM possesses similar long-range correlations. Main et al. showed the slow fall-off of average cumulative correlations with spatial distance found with data from the Gullfaks field in the North Sea, whilst Main et al. related the slow increase in correlation lengths with time (itself power-law function of time, with exponent <0.5; i.e. anomalous diffusion) to the similar behaviour of earthquakes.

**Factor analysis of correlations.** The correlations analysed by either of the above methods are between pairs of wells. There are several ways of extracting a map from this correlation structure. In particular, the matrix that holds all of the correlation coefficients between wells can be decomposed in various ways. To date, the following have been given trial:

- Principal Component Analysis (PCA), which isolates independent modes of rate fluctuation from the correlation matrix, each of which ‘explains’ a certain amount of the variance in the rate fluctuations, quantified by its corresponding eigenvalue. The principal components corresponding to the highest eigenvalues provide, in a rough sense, the most typical sets of rate fluctuations at wells.
- Factor analysis, in which a few factors, not necessarily independent, are fitted to the whole covariance matrix, together with a noise term.
- Principal Oscillation Patterns: this takes into account correlations at zero and one time-lags, such that the time behaviour of the principal components, growing or decaying oscillations, can be determined.

In two cases to date the higher magnitudes within the first one or two principal components have overlain faults, implying that those faults are actively affecting the well-rates. However, further work is necessary to determine which of the above techniques best allows inference of geomechanical behaviour. Using the field correlation data to calibrate other types of geomechanical model also has potential.

**Interpolation of ‘strain’ between wells.** The result of each of the above methods of matrix decomposition comprises a set of vectors, each with values representative of the relative magnitude and sign of fluctuation in rate (or ranked rate) at individual well locations in a reservoir. For each vector these point values need to be interpolated to provide a map. The method of interpolation actually used made the assumption that the rate fluctuations were direct indicators of geomechanical deformation; in particular each value was assumed to be equivalent to the volumetric strain tensor at the well concerned. The form of the spatial correlation of deformation appropriate for a geomechanical system close to a critical point has been formulated. A kriging approach conditioned this spatial correlation structure to punctual well data to provide a minimum variance estimate of the interpolated values of displacement vectors over a grid across the model. From those displacement vectors, other variables of the deformation (principal strains and shear strains) could easily be calculated. The methodology was applied assuming 2-dimensional deformation. Figure 5 shows the results of application to the Gullfaks field of this methodology. Principal components of the matrix of all Spearman rank correlation coefficients that correspond to the first and second highest eigenvalues are seen to overlie gross structural features of the field and its environs. In figure 6 the first 2 principal components of the matrix of Spearman rank correlation coefficients with significance level < 0.001 (99.9% probability) have been superimposed upon a more detailed depiction of the faulting structure. These principal components reflect the similar azimuthal directions apparent in the orientational distributions for the most significant correlations (figure 3) and are therefore potential loci of strike-slip deformation.

**Coupled modelling to test of the concept of near-criticality**

At face value, the long-range, stress-related, fault-related characteristics of the empirical analyses of field data described in section 2 can be explained with the concepts of near-criticality and changing permeabilities outlined in the introduction.
In order to subject this explanation to greater rigour, an investigation was conducted with generic modelling which coupled fluid flow, geomechanical changes and permeability changes: if the same characteristics could be derived from modelled well rates as have been observed in field data, then further strong support would be established for the concept of near-critical, geomechanically-sensitive reservoir mechanisms. The model examined plane strain deformation across an horizontal plane, with strike-slip geometry of induced fault movements. It is quite likely that many fields will experience 3-dimensional deformation, especially where the stress state is borderline between different regimes, as is the case for Gullfaks\textsuperscript{26}. In order to also examine the consequences of deformation in the vertical plane, a cross-sectional model was also studied, in approximate analogy to the gross structure of the Gullfaks field.

**Generic areal model.** A full description of the generic 2D plane strain areal model, the procedure and results, is given in Zhang et al.\textsuperscript{32}. The model contained a generic five-spot waterflood pattern in its central region. Implicit fracture sets across the whole model, and explicit fault zones of low initial permeability also containing further fractures, allowed ample scope for geomechanical activity. A key feature of the model was the relationship between permeability and extensional fracture strain in which permeability rose sharply for normal strains greater than a cut-off value.

At the model boundaries an anisotropic horizontal stress state was applied. A boundary condition of zero displacement was also assumed, which, due to the large extent of the model, had negligible influence on the results. The perturbations to rates associated with changes in well and topside conditions were simulated with random noise input to the well pressures in the model; that noise was spatially and temporally uncorrelated. The consequence flow-rates at wells were calculated from the fluid velocities at the well locations. Then, the correlations over time of flow-rates between each pair of the simulated wells were analyzed with the non-parametric Spearman-rank method. To investigate the effects of stress state on well rate-correlations, three cases were investigated. In the first two cases the boundary stresses were set such as to place the model in a near-critical state, whilst in the third case the boundary stresses made the model sub-critical. The only difference between the near-critical cases 1 and 2 was a variation of 10 degrees between the directions of maximum horizontal principal stress $S_{H}$. In this study the injection pressure was much lower than the confining stress (the minimum total principal stress), so no hydraulic-fracturing occurred. The increase in permeability in the reservoir rocks was due to the dilatation normal to the surface of the faults or fractures, which was caused by the shearing along the faults or fractures in localised shear bands oriented at acute angles to $S_{H}$. Due to the high sensitivity of fracture permeability to strain, such shearing caused significant permeability changes and therefore significant flow rate changes at the wells. The mechanism of long-range rate correlations comprised local hydraulic responses at one well, plus long-range mechanical responses, plus local hydraulic responses at the other well. In this way, correlated flow rates occurred between a pair of wells over a long distance, even though no direct hydraulic links existed between them. In fact, some of the well pairs with high correlations at long-range were separated by low permeability faults. Such long-range rate correlations required the presence of a critical stress state encompassing both wells, when the rocks were strongly susceptible to small perturbations (metastability). It was this mechanism that allowed strong rate correlations to occur over a distributed area under a compressive stress regime in which lateral components of fault displacements could be significant. Note that shear failure in the model was governed, not only by the assumed initial stress state, but also by the cohesions and orientations of the individual faults and fractures and the complexity of the stress state that evolved during production and injection.

For case 3 no shear failure occurred, and therefore no failure-induced permeability enhancement developed. Thus, the permeability of the reservoir rock around the wells remained uniform, and the faults still served as permeability barriers. Under such hydraulic conditions, the flows around the wells were determined by the pressure changes only.

For the two near-critical cases the orientational distribution of correlations showed the same strong bias sub-parallel with the direction of $S_{H}$ (figure 7), whereas the sub-critical case showed no orientational bias. Proportional cumulative correlation coefficients showed only shallow spatial decay approximating a power-law with exponent $\sim -0.7 \pm 0.1$ continuously to the largest separation distance (albeit only 1 order of magnitude of range in distances was available in the model). In contrast, for the sub-critical case 3 the correlations were an order of magnitude lower at short distances, and decayed rapidly even further at larger separation distances. The distance at which the rapid decay began was calculated to correspond to a dimensionless diffusion time of about 0.25, which is the dimensionless time beyond which correlations due to Darcy flow would indeed be expected to rapidly decrease.

Analyses of data from the Gullfaks field can be compared against these numerical results. As well as the long-range Spearman rank correlations indicated in figure 4, the SRM\textsuperscript{32} also yielded apparent power-law spatial decay of correlations, with exponent $\sim -0.5$. The field data showed no sign of dropping away at any distance in the manner of the numerical case 3: in fact, there seems to be a boundary effect that increases correlations for well-pairs as maximum separation across a reservoir is approached.

**Cross-sectional model in analogy of Gullfaks.** Zhang et al.\textsuperscript{37} described this model and its preparation. A key combination was the existence of shallow-dipping faults (formed in the Mesozoic extensional phase of the structural history of the Gullfaks field), and the modern-day stress state that is now compressive and oriented such as to place those faults close to critical. The modelling comprised perturbation of nominal wells in one part of the field, to which the responses across the whole model were observed. Results are qualitatively similar.
to the generic model: displacements occurred on faults at large
distances from the wells being perturbed, but only when the
model was loaded with a stress state that provided near-
criticality on the faults. Interestingly, the cross-sectional
model shows re-activation of the fault that borders the
“domino” and “horst” structures of the field; this fault also
appeared to be a major factor in the rate correlations
determined empirically from the Gullfaks field (figure 8).

Discussion
The long-range correlations in flow rate observed in several
oilfields are consistent with a critical point response involving
hydro-mechanical interactions. The only conventional
explanation for a power-law correlation function, up to a
distance of 10 km, at one month lag or less, would involve the
existence of high permeability channels of sedimentary or
diagenetic origin; however those would provide paths for
extremely early breakthrough of injected fluids that has not
been observed over such long ranges. Also the fact that the
most frequent orientations of correlated well pairs are in
directions likely to be near critical in the present day stress
field argues for a geomechanical mechanism. The generic
coupled geomechanics-flow modelling lends considerable
weight to the geomechanical explanation. Preferentially
oriented breakthroughs of injected fluids along the shearing
directions at small angles to the maximum horizontal principal
stress have been observed, but generally only over short-
range inter-well distances. It is remarkable that concordant
explanations exist for two prominent characteristics in field
data: both in terms of long-range mechanical behaviour, and in
short-range hydraulic behaviour, shearing appears to be a
consistently important reservoir mechanism.

We cannot at this stage rule out for certain the possibility that the
rate correlations at shorter range may in principle reflect a
more conventional reservoir response based on geological
architecture. It should also be noted that the method of spatial
interpolation of strain used tends to emphasise direct paths of
connection between 2 points of either very high or very low
strain; some of the correlations might be effected via more
indirect routes through the structural configuration, but
particularly favouring points that are separated along, for
example, strike-slip directions. A less restrictive method of
interpreting the compliance of the system from the correlations
is currently being researched. In future work it will also be
important to calibrate the method against independent data
from tracer tests, fluid pressure monitoring, 4D seismic
observations, and to compare the results with conventional
reservoir simulation. It will also be important to investigate
whether there are any correspondences between different
categories of responses and different geological
characteristics. Good quality stress measurements are a prime
consideration.

Conclusions
Correlations in well rate fluctuations from several fields with
zero or one time-lags have long-range, stress-related and fault-
related characteristics. These characteristics are consistent
with the response of a system near a geomechanical critical
point, which various observations and theoretical models
indicate is the natural state of the earth’s lithosphere.

The mapped patterns of principal components, derived from
the correlation matrices and interpolated using appropriate
spatial correlation functions, overlie particular faults, implying
that these are especially instrumental in determining the flow-
rate fluctuations in the field; such faults are likely to be
geomechanically active. A reactivated fault can itself be
conductive (although other factors will be involved), but it will
also be a control on more distributed hydro-mechanical
properties throughout the reservoir.

Coupled geomechanical-flow areal modelling of a generic
pattern waterflood has reproduced the long-range, stress-
related, fault-related characteristics of rate correlations
observed in plentiful field data, but only when the model is
loaded to a near-critical mechanical state. The model in a sub-
critical state only exhibits short-range correlations unrelated to
stress or faults.

Coupled geomechanical-flow modelling of a faulted cross-
section, based on the Gullfaks field, also demonstrates long-
range influences including remote activation of a fault that
appears to be important in the correlations derived from the
Gullfaks rate history.

It is unclear how the characteristics of rate correlations, seen
consistently in the data from several reservoirs, can be
reproduced with other than a coupled geomechanical-flow
model; this is particularly true of the long-range nature of the
signals. The mechanism of shearing explains the characteristics
of both rate correlations and flood breakthrough
directionalities observed in many oilfields; the implications
that the latter holds for oil recovery and water production
mean that it is commercially very important to incorporate this
mechanism in reservoir modelling.

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Gullfaks dataset, but since this study was performed “at arm’s
length”, we do not imply that they necessarily agree with our
conclusions.

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Figures

Figure 1. Conceptual diagram of the lobes of dilatational and compressional strain at either end of a single fault (left) undergoing shear. The fault acts to transmit such strains over long distances, whilst the local strain changes are seen as the cause of spatially correlated permeability and therefore rate changes at wells. The deformation may of course be distributed over a more complex system of faults undergoing coherent shears (right).

Figure 2. (adapted from reference 3) Orientational distribution of average t-statistics associated with Spearman rank correlation coefficients of well-rate fluctuations aggregated from 8 field areas, each rotated to be relative to a common direction of SH as shown. Over half a million individual well-pairs are incorporated in this plot. The green distribution refers to raw monthly well-rate histories; whilst the red distribution refers to the higher frequency fluctuations from which the low frequency rate trends have been discarded. The thin black circle shows zero correlation. Note that correlations are on average negative sub-parallel to the minimum horizontal principal stress.

Figure 3. Orientational distribution of average Spearman rank correlation coefficients for the Gullfaks field at various degrees of significance level (indicated in the key). The plots have been azimuthally smoothed. Note that, at the most significant levels (p<0.001), the orientational distribution shows 2 peaks approximately 30 degrees either side of the direction of regional SH; those are the 2 orientations of shear in a strike-slip stress regime.

Figure 4. Variation with spatial lag of the proportion of available well-pairs that correlate at a given significance level (given in the key) as calculated for the Spearman rank correlations for the Gullfaks field. There is little decay of correlations with separation of the well-pairs and even a rise in correlations between wells at the highest separations across the field, especially for the most significant correlations (p<0.001).
Figure 6. Gullfaks field, showing principal components of the matrix of Spearman rank correlation coefficients with significance level < 0.001 (99.9% probability) that correspond to the first (upper) and second (lower) highest eigenvalues. The principal components have been interpolated as described in the text and superimposed upon a more detailed depiction of the faulting structure. These principal components reflect the same trends apparent for the most significant correlations in the orientational distributions of figure 3, and are therefore potential loci of strike-slip deformation.

Figure 5. Gullfaks field, showing principal components of the matrix of all Spearman rank correlation coefficients that correspond to the first (upper) and second (lower) highest eigenvalues (thus representing the modes that account for a significant proportion of the variance in the rate fluctuations). The principal components have been interpolated as described in the text and superimposed upon the gross structural features of the field and its environs (taken from reference 38).

Figure 7. Results of the coupled geomechanical-flow modelling of a generic areal pattern waterflood. Orientational distribution of the t-statistics corresponding to the Spearman rank correlations coefficients calculated from the modelled well-rate fluctuations. For the near-critical cases 1 and 2, their aggregated distribution shows a marked peak sub-parallel to $S_{H}$, as for field data (figure 1). For the sub-critical case 3 the correlations are a lot lower in magnitude and show no such peak.
Figure 8. Gullfaks field. The lower part of the figure shows the volumetric strain response to perturbation of 4 wells in the west of the model when loaded with a high E-W horizontal boundary traction that places the shallow dipping ‘domino’ faults in a near-critical state. Response is particularly seen on the fault bounding the ‘domino’ system to the east, and a response of opposite sense is seen on the faults in the horst system further east. This corresponds to the opposing senses of typical rate fluctuation reflected in the first principal component of the rate correlation matrix (as in figure 5).