B06

Production-induced Capillary Fault Seal Failure – How Common Is It?

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SUMMARY

Introduction

There are widespread anecdotal reports that sealing faults sometimes break down during production, but little evidence, in the public domain at least, to support these reports. In this paper we review the theoretical basis for production-induced capillary (i.e. membrane) fault seal failure, investigate numerical models of the mechanism, and discuss the few published examples where observed production behaviour is attributed to fault seal breakdown in a production context due to pressure depletion on one side of a fault. We conclude that the case for fault seal failure is not, perhaps, as strong as many of us believe it to be.

Theoretical background

It is not at all clear why pressure depletion should cause capillary seal failure. Many of the earlier explanations confuse capillary pressure with across-fault pressure and many of the cartoon scenarios of capillary seal failure of Watts (1987), for example, do not work if capillary pressure is correctly defined as the difference in oil and water pressure adjacent to a fault, and not the difference in pressure across it (e.g. Fig 1a). Further consideration of the illustrated scenario indicates that the so-called sealing fault was never wholly sealing in the first place (e.g. Fig 1b). Therefore interpretations of natural pressure data, which, aided by these simple models might suggesting that fault seal failure has occurred, may instead be a reflection that a non-sealing fault was erroneously identified as sealing in the first place. If the scenario considered is modified to one in which the fault actually is initially sealing (Fig 1c), it is clear that production from one side of the fault cannot increase the capillary threshold pressure towards the condition required for seal failure (i.e. capillary pressure equals or exceeds capillary threshold pressure), without considering local, dynamic, saturation changes.

Irrespective of the recovery mechanism, oil production is fundamentally associated with an overall reduction in the oil saturation of a reservoir. Since a reduction in oil saturation results in a reduction in capillary pressure, it is rather problematic to envision a situation in which oil production can force a capillary pressure to exceed the capillary threshold pressure of a fault. Nonetheless, numerical models in which fault rocks are represented as discrete grid-blocks in conventional production simulation models appear to suggest that capillary seal failure can occur in many simplistic situations (e.g. Fig 2) – how?

Insights from numerical modelling

Most commercial flow simulators use up-stream relative permeability weighting, whereby flow (*q*) of fluid phase *p* between two grid-blocks (from block 1 into block 2) is given by the equation:

$$q_{p12} = T_{12} T_{abs} \frac{k_{rp1}}{\mu_p} dP_p$$

where T is the transmissibility of the connection (a function of the permeability of both cells), T_{abs} is a transmissibility multiplier (which is applied to all fluid phases), μ_p is phase viscosity, dP_p is the phase pressure difference, and k_{rp1} is the relative permeability of block 1. Oil flow from a reservoir cell into a fault cell, in a simulation model using this scheme, is therefore independent of the relative permeability of the fault cell. Hence for a numerical flow model, oil will enter the fault in the first time step of the model in every fault cell in contact with a permeable reservoir cell, irrespective of the capillary pressure or oil relative permeability of the fault cell, if the cell has a lower water pressure than the reservoir rock. This oil however cannot flow out of the fault block in any direction because flow of oil from this block is controlled by the relative permeability of the block to oil, which is zero until its capillary threshold pressure is exceeded. Since oil gradually flows into the block (erroneously) but cannot flow out of it, the oil saturation, and hence capillary pressure, in the block gradually increases until the threshold pressure is reached. At this point oil can start flowing into the next fault grid-block, and the process continues until all grid-blocks are permeable to oil which can therefore flow across the fault despite the capillary pressure adjacent to the fault rock never approaching the threshold pressure (Fig 3a). It is possible to correct for the effect by up-scaling the fault rock effects into the reservoir cell adjacent to the fault, and to use this scheme to produce models in which capillary seal failure due to pressure depletion is accompanied by the expected increase in capillary pressure in the reservoir rock adjacent to the fault (e.g. Fig 3b). The ease with which numerical flow model containing the simplistic (incorrect) approach produce cases in which fault seals apparently fail, compared with the extreme conditions required to produce capillary failure seal failure when the artefact is corrected for, support the conclusion that numerical models incorrectly provide support for capillary fault seal failure as a common reservoir production phenomenon.

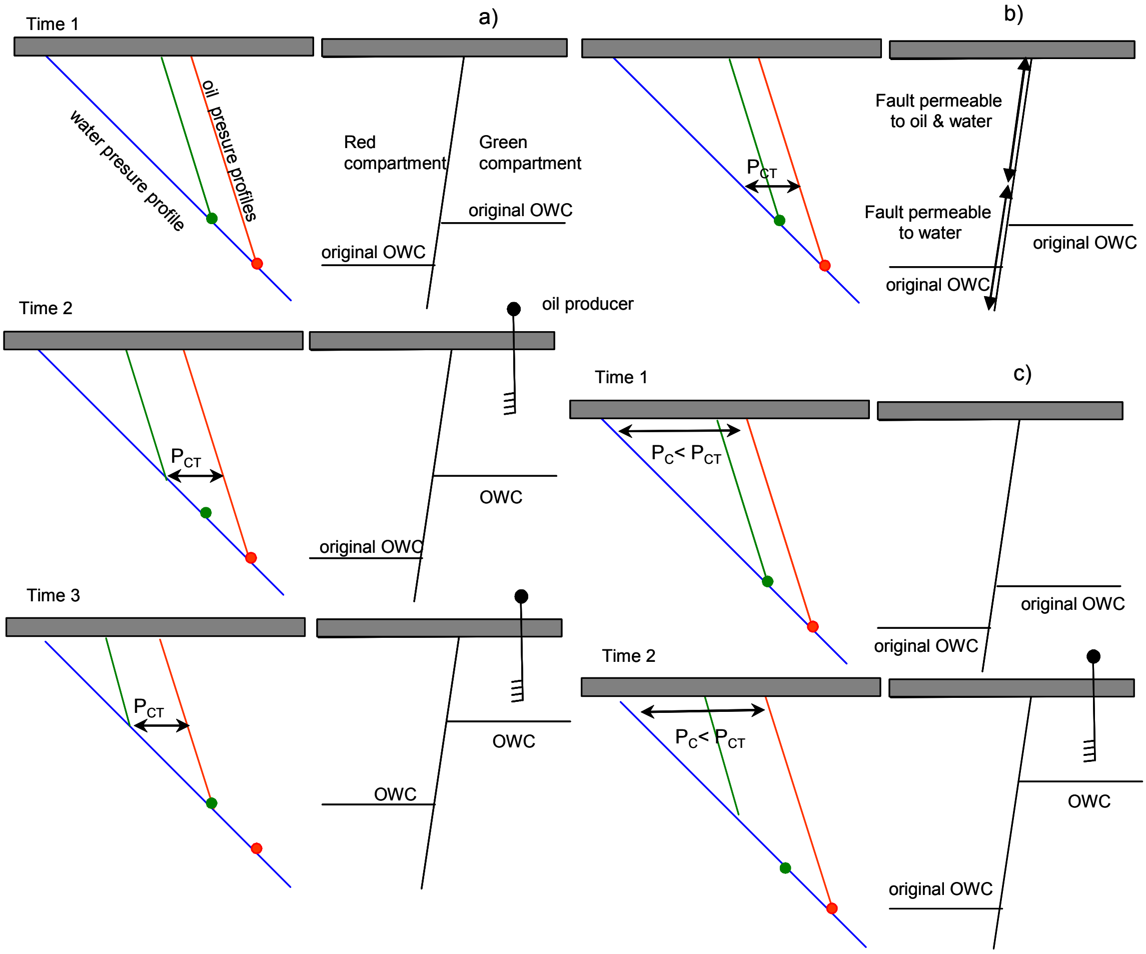

Figure 1 *a) A set of three sequential diagrams purporting to show how pressure depletion on one side of the fault can cause an initially sealing fault to start leaking (redrawn from Watts 1987). At Time 1, a "sealing" fault separates two compartments with different contacts. At Time 2, production from the "green" compartment causes the across-fault pressure difference to equal the fault-rock capillary threshold pressure, causing (according to the theory) the fault to start leaking. Further production (e.g. at Time 3) causes both compartments to deplete together, with a constant across-fault pressure difference maintained by across-fault flow. (b). As pointed out by Fisher et al. (2001) a fault in this configuration would initially be permeable to both oil and water at heights exceeding the distance above the lower OWC at which the capillary pressure on this side of the fault exceeds the capillary threshold pressure of the fault rock, and therefore, as conceptualized, this fault was never entirely sealing to start with. (c) If the capillary threshold pressure of the fault rock is initially greater the largest capillary pressure present (Time 1), then depletion from the green compartment has no influence on the largest capillary pressure present, which remains below the threshold pressure. Depletion from the red compartment (not shown) would actually reduce the capillary pressure, taking the reservoir further away from causing seal failure. The coloured dots show the initial depths of the two OWCs.*

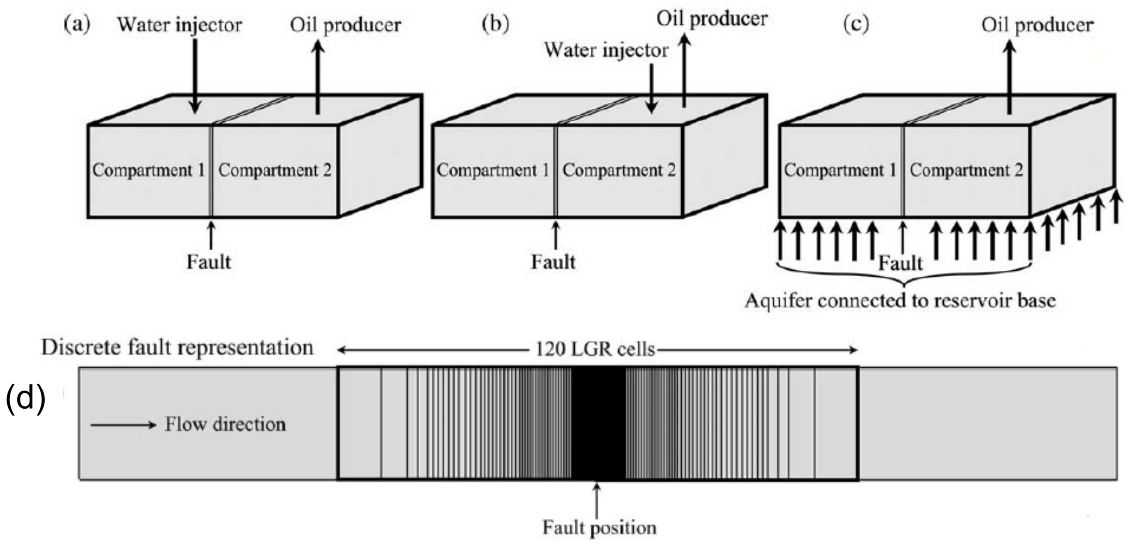

Figure 2 *A set of four simple well configuration examined by Al-Busafi et al. (2005). (a) Water injection and gas production in opposite compartments. (b) Water injection and gas production in the same compartment. (c) Gas production with no injection in the presence and absence of an active aquifer. Fault rock properties (capillary pressure and relative permeability curves) are included in discrete grid-block using local grid refinements (d), and all configurations were modelled with high and low fault rock capillary pressure curves and two fault thickness cases. Despite the fault being initially a seal (i.e. the local reservoir capillary pressure does not exceed the fault rock capillary threshold pressure), in all cases some gas migrates across the fault into the compartment containing the producer. Hence fault seal breakdown is apparently ubiquitous in these models.*

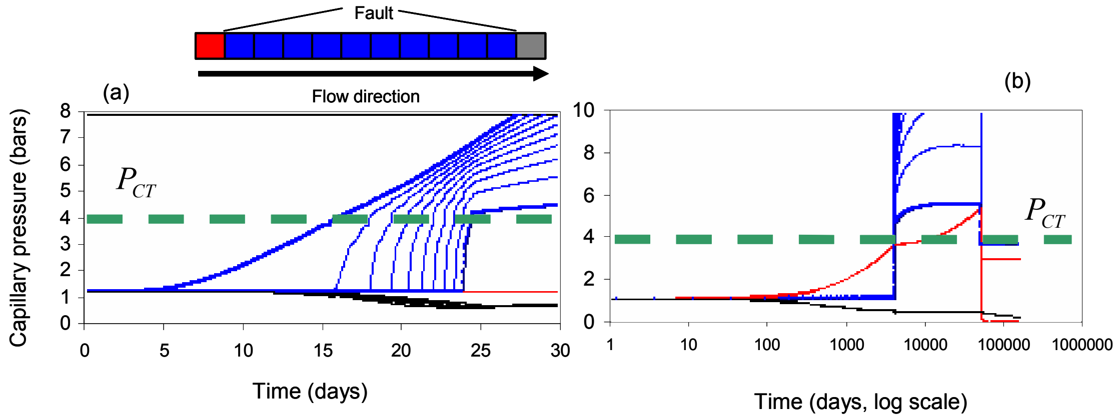

Figure 3 *Flow simulation results for a model with a similar well configuration to Fig 2a. Ten cells are used for the fault rock and are shown in blue. Cells upstream of the fault are shown in red and downstream of the fault in black. (a) shows results from a standard model in which all cells are assigned basic relative permeability and capillary pressure curves appropriate for either fault rock or reservoir rock. Note how the fault cells fail sequentially, with flow into the next one occurring when the capillary pressure of the previous one reaches its threshold pressure (ca. 3.7 bars). By 25 days into the simulation, all fault cells have failed and the fault is permeable to oil despite the capillary pressure adjacent to the fault remaining at its initial value (ca. 1.2 bars). (b) Identical model in which the directional relative permeability of the last reservoir cell has been modified ("pseudoised"; see Manzocchi et al. 2008 for details) to disallow oil flow into the first fault cell unless the capillary pressure of the reservoir cells equals the fault threshold pressure. In this case capillary seal failure still occurs, but does so much later in the simulation history (ca. 10 years rather than 25 days), when the overall depletion of the model is substantial.*

Published case studies

We have been able to find only three publications which attribute observed production behaviour to fault seal breakdown in a production context due to pressure depletion on one side of a fault (Manzocchi et al. 2010). The first example is reported as a case of fault seal breakdown, yet the preferred interpretation of the pressure data by the authors of the paper (Jev et al. 1993) is that the behaviour was caused by across-fault flow in water-leg and there was little (if any) across-fault hydrocarbon flow. The second example (Davies et al. 2003) is a situation in which the hydrocarbon is in a low-pressure compartment and the water pressure gradient within the fault rock into the high pressure compartment supports the column. As the high pressure compartment is depressurised, the capillary pressure in the fault gradually increases until the capillary threshold pressure is exceeded and the fault becomes permeable to oil. Capillary fault seal failure with this pressure configuration is completely plausible, but requires rather specific hydrodynamic conditions. The third reported case (Gilham et al. 2005) concerns a fault with no difference in fluid contacts across it, and for which an initially sealing state was deduced by fluid composition data - recent research on equilibration times suggests that such data should be treated tentatively. Production behaviour indicates that the fault is not sealing, hence this, perhaps is an example of a fault considered to have broken down simply because it was initially though to be sealing. Analysis of published examples is frustrating, since crucial bits of evidence are often not supplied (probably they are unavailable), however it is clear that definitive public domain evidence for a widespread occurrence of production-induced fault seal failure is lacking – does better evidence exist within oil companies?

Conclusions

We have focused on the question of whether production induced capillary fault seal failure is as wide-spread a mechanism as the proliferation of anecdotal reports would suggest. We have concluded that established theoretical models of the mechanism are incorrect, and that a convenient assumption hard-coded into in conventional reservoir simulation software results in fault seal failure occurring much more readily in numerical models than it should do. Whilst there are certainly situations in which fault membrane seal failure is possible and appears to have occurred naturally, in the absence of initial, abnormal pressure compartmentalization we consider that it is as unlikely to be as prevalent as some reports suggest.

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