A Predictor for Accelerated Coupled Rock Mechanics and Reservoir Simulation

Proc. ECMOR X, 10th European Conference on the Mathematics of Oil Recovery
4.-7. Sep. 2006, Amsterdam, The Netherlands

Øystein Pettersen
Centre for Integrated Petroleum Research, Bergen, Norway

Abstract

The impact of the stress field on reservoir fluid flow and production can be significant for many kinds of reservoirs, and hence coupled Rock Mechanics and Reservoir Simulation has been seeing a growing popularity. A much used scheme is *iterative coupling*, where compaction is computed at each stress step by iteratively updating cell pore volumes in the reservoir simulator by values calculated from strain in the stress simulator.
Although the procedure works satisfactory, it may be slow, as often many iterations are needed. Further, the pore volume corrections will only be performed at selected stress time steps, such that pressure and compaction in the flow simulator are not continuous in time. Many reported schemes assume specific poro-elasto-plastic models, as e.g. linear elastic, and also require modification of code.
It is well known that compaction is a function of strain, while reservoir simulators use fluid pressure, the only compaction energy available. On this background few if any coupled procedures utilize the compaction vs. fluid relationship at all.
In this paper we show that the relationship can nevertheless be used as basis for constructing a predictor for the actual stress / strain computations, which leads to significant speed-up. Many of the features of the predictor can be determined from the first stress time step only, and for later stress steps it can be improved with small effort. The scheme is valid irrespective of the poro-elasto-plastic model, and is based on information exchange, so no simulator code modification is necessary.
The compaction state is primarily dependent on the materials, boundary conditions, and the production process, with the geometry dependency as the governing. The predictor is constructed by modifying compaction vs. fluid pressure to take account of geometry variation. A good predictor will result in an improved pressure field as computed by the reservoir simulator, hence providing the stress simulator with a better pseudo-initialiser, such that it converges quicker, and in the pore volume iteration scheme fewer if any iterations are required.
In total we have experienced a reduction in total computer time of more than 90% in some cases, and as a bonus the fluid pressure field is continuous in time.

Introduction

A producing reservoir will be influenced by soil compaction in several ways, e.g. in a depletion process the total available compaction energy will govern reservoir pressure development and thereby production rates and totals.

Conventionally, compaction in a reservoir simulator is modelled as a grid cell pore volume multiplier vs. fluid pressure. This is a simplified model that is used because fluid pressure is the only available parameter for compaction computations in the simulator, and is only partly based on physics, since it does not take account of the reservoir rock behaviour, which may be nonlinear poro-elasto-plastic, depending on stress path, temperature, and possibly water content (Longuemare *et al.* 2002). Volumetric compaction is a function of

effective stress σ, which neglecting grain compressibility is defined as $\sigma = \sigma_T - p_f$, where σ_T is total stress and p_f fluid pressure (Wood 1990). Of special relevance for compaction calculations is the mean effective stress p (the average of the diagonal elements in the stress tensor), $p = (\sigma_{xx} + \sigma_{yy} + \sigma_{zz})/3$, and the volumetric strain ε_p (the sum of the diagonal elements in the strain tensor), $\varepsilon_p = \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}$.

During the last decades there has been a growing awareness that the dynamic stress state in the reservoir often has a significant impact on petrophysics and fluid production, and that this interaction can only be understood by performing coupled rock mechanics and reservoir simulator studies (Koutsabeloulis, Heffer, and Wong, 1994; Settari and Mourits, 1994; Gutierrez and Lewis, 1998; Koutsabeloulis and Hope, 1998; Settari and Mourits, 1998; Mainguy and Longuemare, 2002; Longuemare *et al.*, 2002; Thomas *et al*., 2003). Extending reservoir simulations to also take account of stress state computations will normally increase run time by at least an order of magnitude. Even acknowledging that this is necessary to gain the needed knowledge, there is undoubtedly a need to investigate methods which can reduce overall computing time (e. g. Settari and Walters, 1999).

The ideal manner to simulate the soil–fluid interaction is to solve the full coupled system of stress and fluid flow equations (Settari and Walters, 1999; Gutierrez, Lewis, Masters, 2001; Longuemare *et al.*, 2002; Lewis, Makurat, Pao, 2003). This is, however, complex and time consuming. In addition, currently no fully coupled simulator exists which includes all options provided by the market leading stress simulators or reservoir simulators. Hence, it is interesting to look at the alternative approach of *partial coupling*, where stress state and reservoir fluid dynamics are computed by dedicated software with data exchange at chosen time steps, called *stress steps* (Gutierrez and Lewis, 1998; Longuemare *et al.*, 2002; Mainguy and Longuemare, 2002; Thomas *et al.*, 2003; Dean *et al.*, 2003). In *explicit* coupling the data exchange is one-way only. First the flow simulator is run a time interval ending with the stress step. Then the simulated fluid pressure and saturations are used to initialise the rock mechanics simulator, which computes the stress state at the time. This computed stress state is further used to update the flow simulator data (typically porosity or / and permeability) where after the flow simulator progresses the solution in time to the next stress step (Heffer *et al.*, 1992). The explicit scheme provides a qualitatively correct stress and compaction distribution, but the *level* is generally not correct. Therefore the explicit scheme has been improved by iteratively updating the flow simulator cell pore volumes by the values calculated by the rock mechanics simulator at the stress step until convergence, *iterative* coupling (Settari and Walters, 1999, Chin *et al.*, 2002, Onaisi *et al.*, 2002; Tran, Settari, Nghiem, 2004). As noted by Settari and Walters (1999), iterative coupling is as accurate as full coupling if taken to full convergence, but can be very costly in terms of computing time.

Preliminaries

In this paper we will investigate the relationship between the true compaction values computed from strain and those computed from fluid pressure, and demonstrate how the flow simulator pore volume compressibility concept can be modified such that both each stress step computation time and the number of iterations in an iterative scheme can be greatly reduced, hence reducing overall processor time considerably.

Some of the referred coupling schemes are based on code modification in the flow simulator or / and the stress simulator, and some are restricted in the choice of poro-elasto-plastic model (e.g. linear elastic). The presented scheme is valid for a general poro-elasto-plastic model and does not require any code modification – based purely on data exchange between commercial simulators (Schlumberger 2005; VIPS 2003).

We will use m, the ratio of current to initial cell pore volumes (denoted *pore volume multiplier*) as a measure for compaction. The flow simulator computes compaction from functions (tables) of pore volume multipliers vs. fluid pressure, while in reality m is a function of mean effective stress p. Further, for a deforming rock, the compaction of a control volume

can be computed from volumetric strain. To distinguish between these different sources for m we define the following notation,

m_{pf} m is a function of fluid pressure, as used by the flow simulator.

m_p m is a function of mean effective stress

m_ε m is computed from volumetric strain, $m_\varepsilon = \exp(\varepsilon_p^0 - \varepsilon_p(t))$, where ε_p^0 and $\varepsilon_p(t)$ are volumetric strains initially (no load) and at time t. Provided calculated strains are correct, this m-function represents the true compaction to which other values will be compared.

The notation m_{pf} will be used both to denote the function (table) used in flow simulation, and for grid cell values of m derived from this function (similar for m_p).

The function $m_p(p)$ can be the result of laboratory experiments, but can also be derived from the poro-elasto-plastic model, which is the chosen method for the reported simulations in this paper.

When discussing compaction energy (p_f or p) or compaction we will use the term *level* to denote an absolute value of the magnitude (as e.g. the average cell value) and the term *distribution* to denote (in a non-strict fashion) how the parameter varies in the reservoir. Obviously the reservoir energy or compaction state is correct if and only if both level and distribution are correct.

With this notation the iterative scheme can be characterised by, following a stress step, m_{pf} is set equal to m_ε (calculated by the stress simulator) in all grid cells, and the cycle "flow simulation – stress simulation – pore volume update" is repeated until $m_{pf} \approx m_\varepsilon$ everywhere. Since changing pore volumes in the flow simulator results in an altered fluid pressure field, the calculated m_ε will also change, which explains why the convergence is often slow. Clearly, the convergence will be much faster if the flow simulator computed pressure and compaction state approximates the true (final) state computed by the stress simulator. The motivation for the procedure presented in this paper is hence to improve the compaction / pressure state used as initialiser for the stress computations, which is done by modifying and extending the flow simulator compressibility functions to include a spatial dependency which honours the true space variation as computed by the stress simulator.

Fluid pressure and mean effective stress

In a coupled simulation model, large volumes of over-, under-, and sideburdens are normally included, with rock mechanics boundary conditions that constrain the model edges (far from the reservoir). Thereby the interaction between porous and non porous rock is honoured, as e.g. the influence of the surrounding soil on reservoir deformation. It is well known that basing compaction calculations on fluid pressure as in a flow simulator where this interaction is missing, will be inaccurate. A simple illustrative example is shown in Figure 1, depicting computed compaction from fluid pressure (A) and the true value from strain (B), for a depletion process in a box-shaped reservoir with a row of injectors along the western edge and a row of producers along the eastern. As shown in Figure 2, the vertical displacement in the reservoir is non-uniform, causing a corresponding compaction field which cannot be reproduced by the fluid simulator, at least not by a conventional compaction model. Omitting the rock mechanics influence will also often result in an inaccurately simulated flow pattern, due to permeability reduction in compacted volumes. For the same example as in Figures 1-2, using the compaction field calculated by the flow simulator m_{pf} results in a piston-like fluid front movement (Figure 3A), while using the accurate compaction field m_ε the simulated fluid front shape is as depicted in Figure 3B.

For a more realistic example, Figure 4 shows the resulting compaction fields m_{pf} (A) and m_ε (B) for a fractured chalk reservoir with several different material types. Although more complex we can clearly see that the true compaction state is to a large degree influenced by material boundary effects, both internal and external. So although a number of parameters contribute to the final stress and compaction state, studies of both simple and complex reservoir models indicate that the difference between m_{pf} and m_ε to a large extent can be

explained by the material to material interaction, geometry, and non-reservoir soil boundary conditions.

For clarity of presentation we will restrict the discussion to the simple model above in the following. The main difference for multi-material models is that internal material boundaries must also be accounted for.

Mechanisms of coupling

Using **x** to denote position, the fluid pressure and compaction state $(p_f(\mathbf{x}), m_{pf}(\mathbf{x}))$ at a stress step (as exemplified in Figure 1A) is input to, and used as start values for the stress computations by the rock mechanics simulator, which calculates the resulting compaction state (as in Figure 1B). This compaction state will be a function of soil properties and the production scheme as discussed above. Many of the qualitative features of the compaction distribution are primarily determined by *static* soil properties, as the poro-elasto-plastic model, geometry, and soil behaviour in the surrounding non-porous rock, defining a quasi-static compaction *distribution*. On the other hand, the compaction *level* is primarily determined by the dynamic process, which obviously also influences the distribution, but in general this influence is smaller than the static contribution. E.g., altering m_{pf} will change the flow simulator fluid pressure level, and hence the choice of m_{pf} has direct influence on the stress simulator computed compaction level in an explicit scheme. By iterative coupling the compaction level is then subsequently converged to its correct value. This was also noted by Mainguy and Longuemare (2002) (and others), "the pore volume compressibility in conventional reservoir simulation is a parameter determined by the reservoir engineer, which can be considered a numerical parameter, since whatever the value supplied by the reservoir engineer, the rock mechanics simulator will provide the exact porosity." They also demonstrate that the number of iterations needed in an iterative coupling scheme may be very sensitive to this parameter. Apart from this observation there seems to be no attempt to utilise the "compressibility parameter" to increase the efficiency of coupled simulations in the referred papers.

A first attempt at speeding up the computational scheme could be to try to determine an "optimal" pore volume compressibility. Since the flow simulator computed compaction distribution is so far from the true distribution, it is however not obvious what would be an optimal value, if such a value exists. On this background we propose to extend the conventional concept of pore volume compressibility used by the flow simulator to a compressibility function $m^*_{pf}(\mathbf{x}, p_f)$, that for fixed **x** will have a pressure dependency that is determined by scaling of the original $m_p(p)$, and a spatial variation which honours the compaction distribution computed by the stress simulator. Both the level and distribution of this function can be determined from the results of the first (explicit) stress step (as in Figure 1B). If correctly tuned, the compaction state computed by the flow simulator based on $m^*_{pf}(\mathbf{x}, p_f)$ will be close to the true compaction state, hence the rock mechanics simulations converge faster, both for each stress calculation, and with respect to total number of pore volume iterations needed.

Also note that with a conventional iterative scheme, fluid pressures and pore volumes will only be correct at the stress steps, while if the compressibility parameter is inconsistent with the poro-elasto-plastic model, the flow simulator computed pressure development between stress steps will be wrong, with artificial "adjustment" discontinuities at the stress steps (Figure 5). This "feature" can be reduced or removed if the flow simulator uses a compaction model that results in a compaction field which is in agreement with the stress simulator computed field.

Local behaviour – Extended compaction functions

Although no simple relation exists between mean effective stress and fluid pressure, the preceding discussion motivates an assumption that p and p_f can be related *locally*, i.e. for a fixed position **x**, $p(\mathbf{x}) = p(p_f(\mathbf{x}))$. From (iterative) coupled simulations with varying kinds of

material data we have examined the behaviour of p versus p_f in single cells, and found that in general the assumed relation does exist, at least approximately. An example is shown in Figure 6. Motivated by this observation and requiring that the extended functions should be easy to construct, we propose a *predictor* for the rock mechanics calculations.

Predictor – extended compaction functions

Locally, i.e. for a fixed **x**,

i. $p(\mathbf{x}) = p(\, p_f(\mathbf{x}))$

ii. $m^*_{pf}(\mathbf{x}, p_f)$ is a scaled version of $m_p(\, p)$ (i.e. shape is conserved)

The novel concept here is that the extended flow simulator compressibility function $m^*_{pf}(\mathbf{x}, p_f)$ also honours the spatial variation found by the stress simulator. (Note: The spatial variation described here is for a single material, which we have restricted ourselves to in this discussion. Generalisation is straightforward.)

An essential feature of the extended compressibility functions is that for fixed **x**, they can be found by a simple shape-conserving transformation of $m_p(p)$. Details of this transformation and the scaling process will be reported in a later paper.

If the predictor is exact, the extended compressibility function can be computed at the first stress step, and thereafter an accurate compaction state can be computed (by the flow simulator) from the fluid pressure state *at all subsequent stress steps*. In each grid cell, the flow simulator computes a pore volume multiplier and fluid pressure from the local compaction relation valid for the cell in question, constructed by assumption ii). Then the corresponding mean effective stress computed from assumption i) will be in agreement with the rock mechanics simulator computed p, and hence $m_{pf} = m_\varepsilon$ in the cell.

Obviously, in general, the predictor will not be exact, but our experience is that the cell m_{pf} computed by the predictor algorithm will generally be a good approximation to the actual multiplier, and at least significantly better than the conventional flow simulator pore volume multiplier. When the flow simulator computed compaction state is close to the true state, and this state is used as initialiser for the rock mechanics simulator, stress computations will necessarily converge faster.

The predictor is constructed at the first stress step, but updated following each stress calculation in order to honour the most recent results. If this update changes the predictor "significantly", it can be advisable to rerun the latest stress step. By the algorithm, this second run *will* converge to the correct compaction state, such that only in exceptional cases will further iterations be needed. (We have never encountered such a situation in our example runs.)

Additionally, since the extended compressibility function is used by the flow simulator for calculations between stress steps, and compaction state is (almost) correct at the stress steps, fluid pressure and compaction development will be (nearly) correct and continuous at all times.

Pseudo material regions

In practice it is not necessary to use one compressibility function for each grid cell, which would also be memory-requiring for large grids. Instead, each original material region is subdivided into several *pseudo material regions*, each with its own compaction function, such that all cells in a pseudo region have almost equal compaction functions, approximated by the common pseudo region compaction function. The number of such pseudo regions is determined by an error tolerance. In practice we have found that no more than 20 pseudo-regions are needed, often fewer. An example is shown in Figure 7. With only one material originally, the single parent material region is comprised of the entire reservoir. Ten pseudo material regions were constructed based on results from the first stress step, and the resulting regions in one reservoir layer are shown in Figure 7A. Each of these regions is associated with one extended compaction function $m^*_{pf}(p_f)$, constructed by scaling the original $m_p(\, p)$. The ten extended compaction functions (vs. fluid pressure) and the original $m_p(p)$ (versus mean effective stress) are shown in Figure 7B.

These pseudo material regions and compaction functions were then used in the flow-simulator. The flow simulator computed compaction state m_{pf} at a later stress step (3) is shown in Figure 8A, which should be compared to the resulting m_{ε} computed by the rock mechanics simulator, Figure 8B. This compaction state has correct level, and was found without iterations. Note that Figures 8A and B are not identical, which they would be if the predictor was exact, but the state in Figure 8A is an excellent starting point for the rock mechanics simulator solver.

Computer performance – experience

The procedure requires an additional run at the first stress step, the tuning run. For the remaining stress steps, only one stress simulation is required – exceptionally one (and one only) extra stress simulation will be needed. Hence, most of the "hard work" is done on the first stress step, later stress steps will typically be at most as processor demanding as explicit coupling. We have run a number of cases with varying material definitions, both single material and multi-material problems. For testing purposes all runs were run as iteratively coupled, but in no cases more than one iteration was needed on any stress step.

Our experiences with respect to computing time are that, i) the rock mechanics simulator converges faster at each stress step due to the predictor, typically more than a 50% reduction, ii) the need for pore volume iterations is eliminated, or at least greatly reduced, which in the extreme can reduce total computing time by more than 95%, iii) the compaction state is very accurately modelled in the flow simulator (i.e. between stress steps).

Conclusion

The compaction state computed by a flow simulator (based on fluid pressure) is very different from the actual compaction state calculated from strain, which in many cases will result in an erroneous fluid flow pattern if simulated by a flow simulator only. This will be especially relevant for reservoirs containing weak sands or many chalk reservoirs. Further, due to this large difference, the flow-simulator calculated compaction state is typically not a good initialiser for the stress calculations. Extending the conventional concept of flow simulator compaction functions to functions which also are space and time dependent, and optimising these by the stress simulator results, significantly more accurate compaction calculations have been achieved already from the flow simulator, which in exceptional cases can be used as they are, or normally act as an excellent predictor for the rock mechanics simulator calculations, hence reducing processor time for this simulator considerably.

References

Chin, L.Y., Thomas, L.K., Sylte, J.E., Pierson, R.G., 2002. Iterative Coupled Analysis of Geomechanics and Fluid Flow for Rock Compaction in Reservoir Simulation, *Oil & Gas Science and Technology – Rev. IFP,* **57**, 485-497

Dean, R. H., Gai, X., Stone, C. M., Minkoff, S. E., 2003. A Comparison of Techniques for Coupling Porous Flow and Geomechanics. Paper SPE 79709, *SPE Reservoir Simulation Symposium,* Houston, Texas, Feb. 3-5, 2003

Gutierrez, M. & Lewis, R. W., 1998. The Role of Geomechanics in Reservoir Simulation. Paper SPE/IRSM 47392, *Proc. Eurock 98, 2,* Trondheim, Norway, July 8-10, 439-448

Gutierrez, M., Lewis, R. W., Masters, I., 2001. Petroleum Reservoir Simulation Coupling Fluid Flow and Geomechanics. *SPE Reservoir Evaluation & Engineering*, June 2001, 164-172

Heffer, K. J., Last, N. C., Koutsabeloulis, N. C., Chan, M., 1992. The influence of natural fractures, faults and earth stresses on reservoir performance – analysis by numerical modelling, *Proc. 3rd International Conference on North Sea Oil and Gas Reservoirs,* Trondheim, Norway, Nov. 1992.

Koutsabeloulis, N. C., Heffer, K. J., Wong, S., 1994. Numerical Geomechanics in Reservoir Engineering, *Comp. Methods and Advances in Geomech.,* Siriwardane & Zeman, eds., Balkema, Rotterdam, 2097-2104

Koutsabeloulis, N. C. & Hope, S. A., 1998. "Coupled" Stress/Fluid/Thermal Multi-Phase Reservoir Simulation Studies Incorporating Rock Mechanics. Paper SPE/IRSM 47393, *Proc. Eurock 98, 2,* Trondheim, Norway, July 8-10, 449-454

Longuemare, P., Mainguy, M., Lemonier, P., Onaisi, A., Gérard, Ch., Koutsabeloulis, N., 2002. Geomechanics in Reservoir Simulation: Overview of Coupling Methods and Field Case Study, *Oil & Gas Science and Technology – Rev. IFP,* **57**, 471-483

Lewis, R. W., Makurat, A., Pao, W. K. S., 2003. Fully coupled modeling of seabed subsidence and reservoir compaction of North Sea oil fields, *Hydrogeology Journal* (**11**) 2003, 142-161

Mainguy, M., Longuemare, P., 2002. Coupling Fluid Flow and Rock Mechanics: Formulations of the Partial Coupling between Reservoir and Geomechanical Simulators, *Oil & Gas Science and Technology – Rev. IFP,* **57**, 355-367

Onaisi, A., Samier, P., Koutsabeloulis, N. C., Longuemare, P., 2002. Management of Stress Sensitive Reservoirs Using Two Coupled Stress-Reservoir Simulation Tools: ECL2VIS and ATH2VIS, SPE 78512, *10. Abu Dhabi Intl. Petroleum Exhibition and Conference,* Oct. 13-16 2002.

Schlumberger 2005, ECLIPSE Reference Manual

Settari, A. & Mourits, F. M., 1994. Coupling of geomechanics and reservoir simulation models, *Comp. Methods and Advances in Geomech.,* Siriwardane & Zeman, eds., Balkema, Rotterdam, 2151-2158

Settari, A. & Mourits, F. M., 1998. A Coupled Reservoir and Geomechanical Modeling System, *SPEJ* Sept. 1998, 219-226

Settari, A., & Walters, D. A., 1999. Advances in Coupled Geomechanical and Reservoir Modeling With Applications to Reservoir Compaction, Paper SPE 51927, *SPE Reservoir Simulation Symposium,* Houston, Texas, Feb. 14-17, 1999

Thomas, L. K., Chin, L. Y., Pierson, R. G., Sylte, J. E., 2003. Integrating Geomechanics in Full-Field 3-D Reservoir Simulation – Modeling Techniques and Field Applications, Paper SPE 77723. Presented at SPE Appl. Techn. Workshop, Corpus Christi, Texas, Jul. 31 – Aug. 1, 2003

Tran, D., Settari, A., Nghiem, L., 2004. New Iterative Coupling Between a Reservoir Simulator and a Geomechanics Module, Paper SPE 88989, *SPEJ,* Sept. 2004, 362-369

VIPS, 2003. The VISAGE™ System User's Guide, V.I.P.S. Ltd.

Wood, D. M. 1990. Soil Behaviour and Critical State Soil Mechanics. Cambridge University Press

Figures

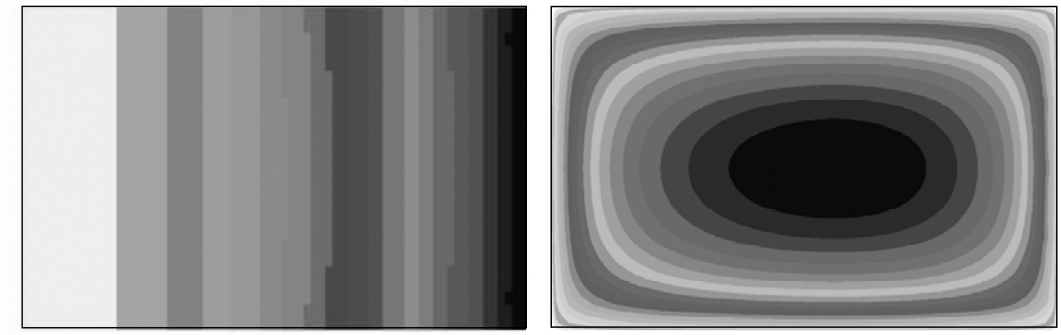

Figure 1. Isocontours compaction, Stress step 1, middle layer. A) Computed from fluid pressure by conventional fluid simulator model. B) Computed from strain by stress simulator

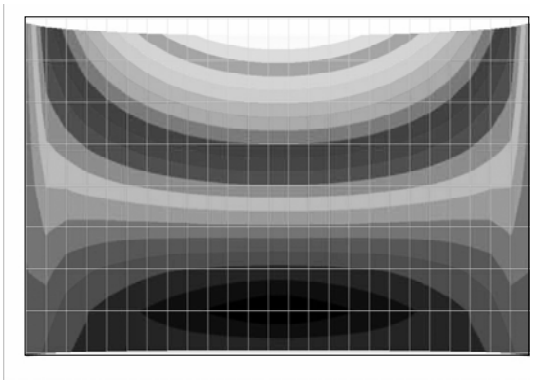

Figure 2. Vertical displacement (reservoir only), side view, centre of reservoir

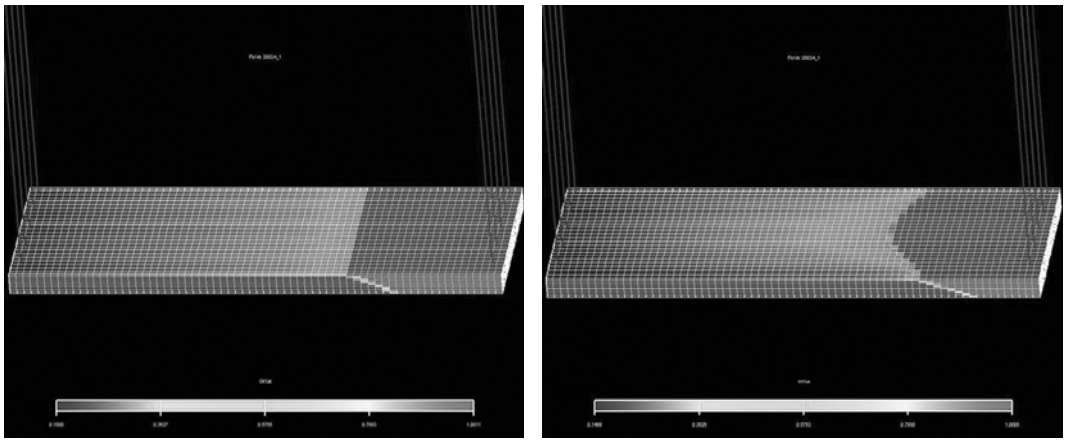

Figure 3. Oil saturation, compaction from fluid pressure (A) and from strain (B)

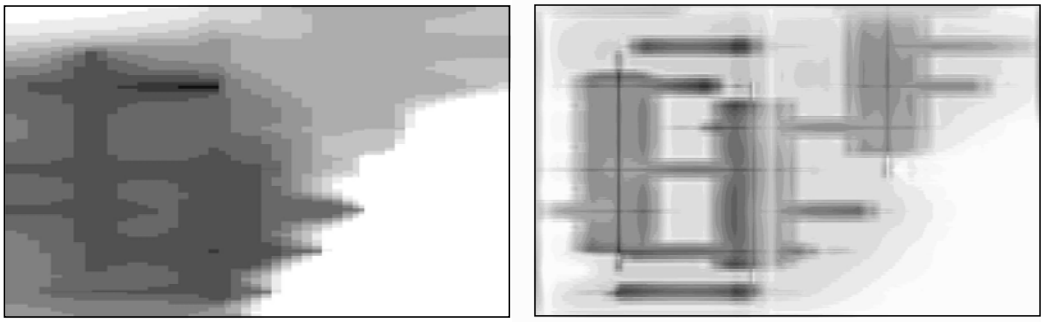

Figure 4. Isocontours pore volume multipliers, base of reservoir, fractured chalk. A) Computed from fluid pressure by flow simulator. B) Computed from strain by stress simulator

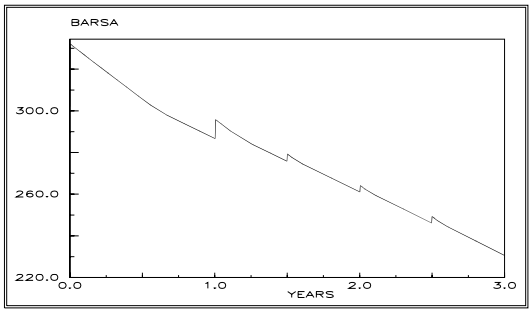

Figure 5. Fluid pressure vs. time, iterative coupling

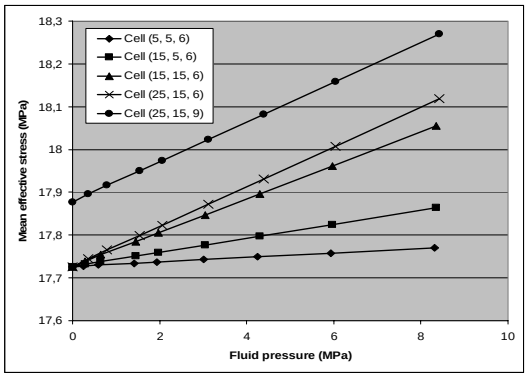

Figure 6. Mean effective stress vs. fluid pressure for some (single) cells

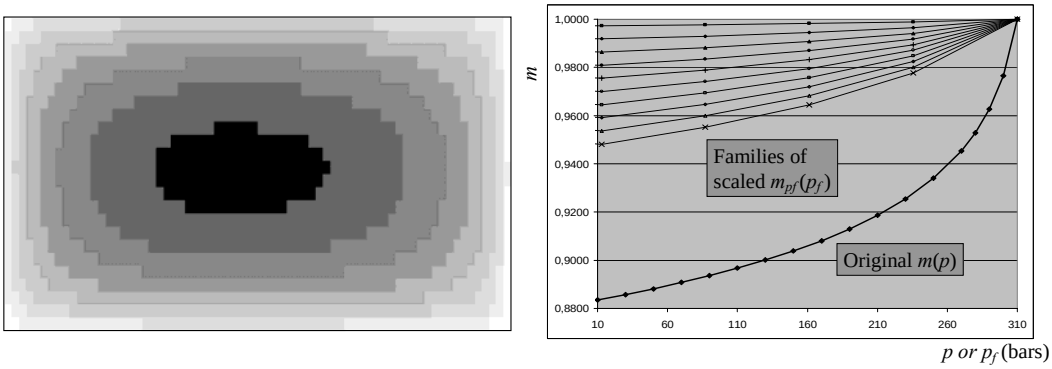

Figure 7. A) Pseudo material regions, middle layer. B) Extended compressibility functions associated with regions in A).

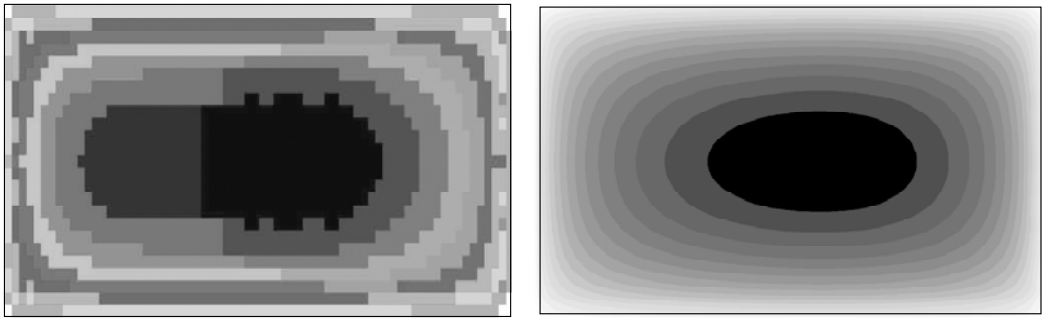

Figure 8. Isocontours pore volume multipliers, stress step 3, area view. A) Computed from fluid pressure by extended compressibility functions in fluid simulator. B) Computed from strain by stress simulator using A) as initialiser