

WS14 B02

R-factor Recovery via Geertsma's Pressure Inversion Assisted by Engineering Concepts

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SUMMARY

A technique is developed for a North Sea chalk reservoir to estimate the Hatchell-RØste R factors using a reservoir engineering constraint. This provides a way of defining the uncertainty on the R values, given the range of mechanical properties for the field of interest.

In our case study the average R for the reservoir and overburden appears to be in the range 7 to 22. R factors are also calculated for regions of pressure relaxation and drawdown identified in the field, and the results confirm the current understanding determined by laboratory experiment and previous studies that the magnitude varies as a function of strain polarity, with the asymmetry being at most a factor of three. These results are validated with full geomechanical modelling followed by time shift modelling, showing that the observed time shifts cannot be created unless this asymmetry is present

Introduction

Production or injection of fluid volumes in a hydrocarbon reservoir leads to subsurface deformation and changes in the strain state not only of the reservoir, but also the surrounding rocks. It has been demonstrated in several field studies that summation schemes based on Geertsma's analytical solution are capable of modelling this strain distribution (e.g. Toomey et al. 2015), and also inverting for changes in reservoir pressure from time-shifts measured by time-lapse seismic data (Hodgson et al. 2007). These schemes provide a simple yet effective approach for tackling the small to moderate magnitude strains detected in many applications of time-lapse seismic data. Following this approach, this current study utilises time-lapse seismic signals in the overburden to estimate vertical strain, and thus invert for reservoir pressure changes at a chalk field in the Norwegian Sea. We find that one benefit of using the Geertsma based inversion is that R-factors can be quantified when prior constraints are available from a well history matched simulation model, and their uncertainty defined. Our results indicate that the magnitude of R is a function of strain change polarity, and that this is indeed necessary to simulate the observed time shifts.

Theory and method

Our starting point is the work of Hodgson et al. (2007) and Garcia and MacBeth (2013), who developed a method for estimating reservoir pressure changes ΔP from measured volumes of seismic time-shifts in the overburden. Central to these methods is the Geertsma (1973) nucleus of strain model that is used to calculate total subsurface displacement by superimposing the influence of many such pressure contributions (see for example Segall 1992). This problem is solved numerically as a system of linear equations by summing contributions from pressure sources on a grid weighted according to a known set of Green's functions, G_{ij} , dependent on the location of the individual sources, and also on the average shear modulus and Poisson's ratio of the subsurface. The equation (1) links each estimated vertical strain $\varepsilon_{zz,i}$ in a cellular volume of M cells to the reservoir changes ΔP_j in a grid of N cells

$$\varepsilon_{zz,i} = \sum_{j=1}^M G_{ij} \Delta P_j. \quad (1)$$

To relate vertical strain changes to the fractional velocity changes, and hence measured time-shifts, the R factor model of Hatchell and Bourne (2005) is now commonly employed. These factors can be measured directly in the laboratory (Holt et al. 2013) or inferred by comparing measurements from observed 4D seismic data to modelled geomechanical deformations (Hatchell et al. 2003), but consensus on the exact values to use has not yet been reached and they may still be considered uncertain. Unlike full geomechanical simulation, the formulation in (1) provides an opportunity to close the loop between the measured time shifts and pressure changes in a quick modelling and inversion study. It is then possible to build up statistics to quantify the R factors by using some knowledge of the pressure changes from a well-conditioned simulation model as a constraint, combined with a range of subsurface mechanical properties. The simulator honours material balance in the reservoir and is adequately matched to the historical well data via history matching. Therefore it is assumed that the resultant pressure predictions are at least statistically accurate, and should possess more accuracy than an R factor guess for a particular field. The R factors are determined by scaling the pressure change solution such that the histograms of pressure estimated from the inversion scheme and the predictions from the simulator coincide.

Application to a chalk field

The above methodology is applied to a geomechanically active chalk reservoir. During the seismic monitoring period, injection is carried out for pressure maintenance and an understanding of pressure changes will help to understand the overall performance of the wells. The pressure inversion is

applied to both seismic vintages acquired two and a half years apart. For input into the inversion, time-shifts are selected at four horizons in the overburden. Figure 1(a) shows the time shifts in the overburden interval above the reservoir. These horizons are chosen based their distance from the reservoir, the need to include as much data as possible, and the signal to noise ratio at each. As in previous implementations, the inversion is solved using a standard least squares objective function with a smoothing constraint (but no constraint from the simulation model predictions) – the typical

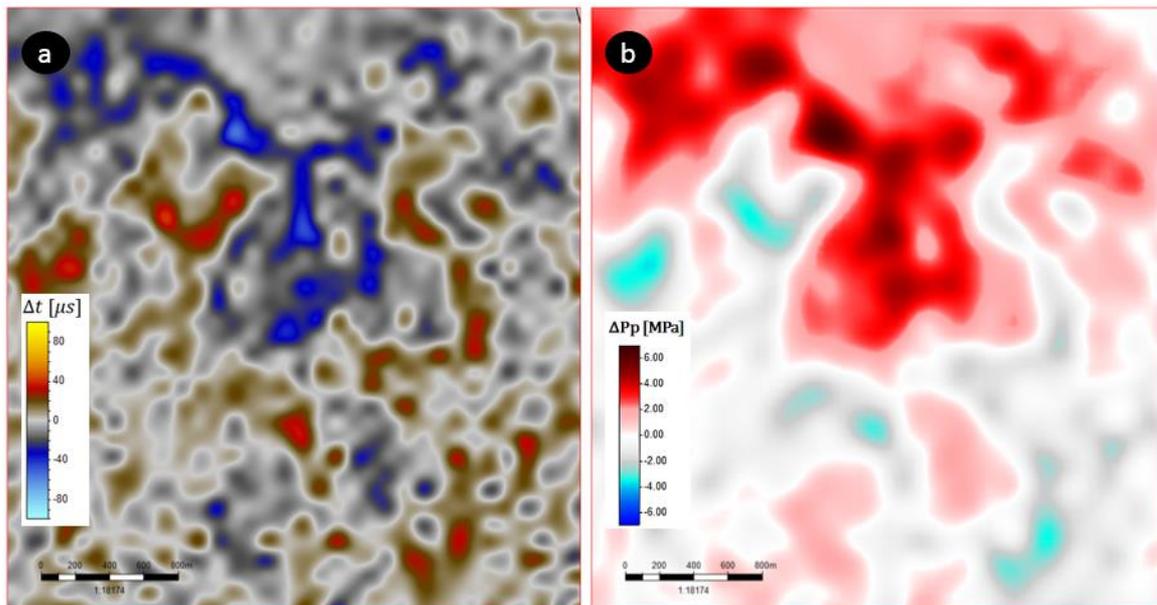


Figure 1 Maps of (a) time shifts in the overburden and (b) the Geertsma inverted reservoir pressure change. In (a), red signals signify an increase in travel time, or expansion, whilst the blue signals indicate a decrease in travel time, or compaction.

result for an average R-factor is displayed in Figure 1(b). According to the Geertsma formulation, the inverted pressure change also scales with the choice of the shear modulus and Poisson's ratio assigned to the average half-space representing the reservoir and overburden. This therefore poses an interesting possibility: the best choice R factor can be found by performing many inversions for different combinations of shear modulus (μ) and Poisson's ratio (ν), and then finding the R that matches the estimates to the simulator predictions (matching the means of the histograms). In this case study a range of lithology dependent mechanical properties are available from the Valhall field (Zhang et al. 2011). A half-space consisting of 100% shallow shale ($\mu=0.10\text{GPa}$ and $\nu=0.20$), soft chalk ($\mu=0.56\text{GPa}$, $\nu=0.17$), compacted shale ($\mu=0.58\text{GPa}$, $\nu=0.25$), and stiff chalk ($\mu=1.86\text{GPa}$, $\nu=0.19$) are all considered initially, together with a range of properties between these end points. The inversion with scaling adjustment gives R factors of 127, 19, 22 and 7 for the four end member property pairs however a half-space of all shallow shale is considered unlikely. The spread of R factors recovered for different material properties helps define a range of possible uncertainty (see dotted black line in Figure 2). The final result in Figure 1(b) is determined by using a property average that is an equal weighting of all four end-points ($G=0.78$, $\nu=0.20$), for which an R factor of 16 is recovered.

Hatchell and Bourne (2005) proposed an asymmetric R as a function of strain polarity as a way of interpreting the magnitude of the observed time shifts with different observed strain deformations. Rocks that are undergoing an extensional strain change (often in overburden rocks) show larger fractional velocity changes in comparison to regions with those undergoing compressive strain changes (often, but not exclusively, in the reservoir). This behaviour is also similar to that observed in laboratory measurement. For example Holt et al. (2013) find that the R factor of a rock that has gone through an initial cycle of depletion followed by re-pressurisation is different compared to the same

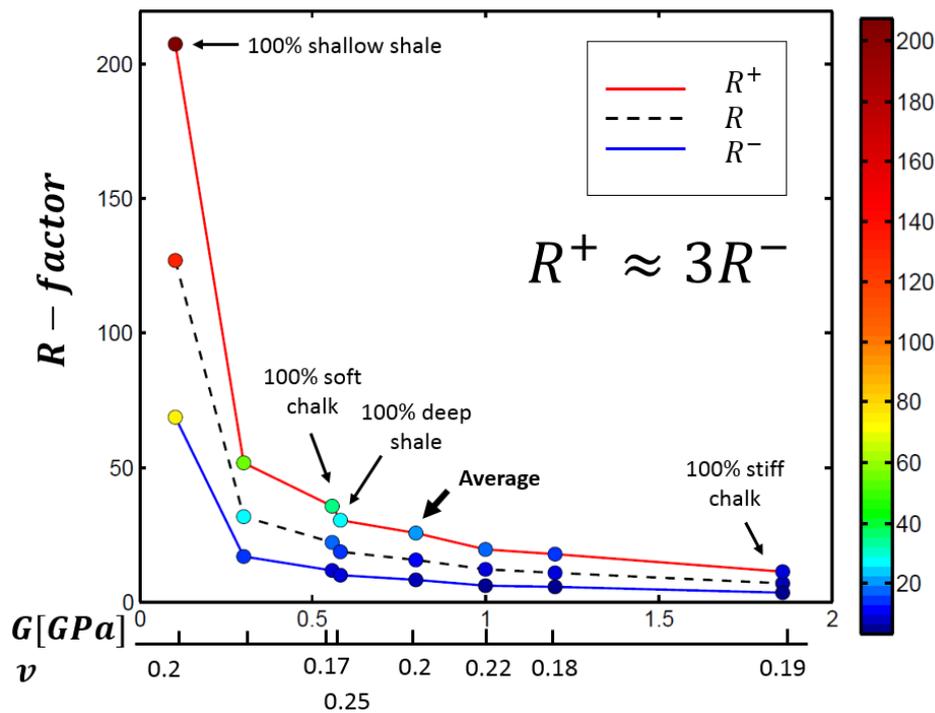


Figure 2 R factor results corresponding to the different lithologies in our field study.

rock undergoing only injection; suggesting possible excess deformation due to internal defects from the first process. This understanding can be tested in our current dataset by selecting two regions with different production/recovery mechanisms, predominantly influenced by either reservoir depletion or pressurisation. R factors are calculated by independent inversion of each region, using the average mechanical properties from the previous study. In order to ensure minimal overlap between these areas of pressure up and down, the regions are selected around wells. The results of this process are also shown in Figure 2, these indicating that the R for expansion (R^+) is 3 times larger than that for compression (R^-) – a similar asymmetry to that quoted in the previous publications. To validate this finding for our particular field, time shift modelling is performed using a synthetic fluid flow simulation and a full geomechanical model with similar properties to the field. The flow simulation model consists of two injectors and one producer with similar production history to the actual wells. For the geomechanics, the reservoir model is fully encased in a shale overburden, sideburden and underburden. Mechanical properties are assigned according to Zhang et al. (2011). The time-shifts are calculated by converting physical strain to velocity change, assuming both symmetric and asymmetric R factors. Figure 3(a) gives the results for $R^+ = R^-$, and Figure 3(b) for the case of $R^+ = 3R^-$ determined from our previous findings. The asymmetric R factors produce time shifts that appear more consistent with the real field observations. A positive time shift is generated below the reservoir, implying a strong accumulation of time shift in the overburden relative to that in the compacting reservoir. This would not be the case unless the R factor is asymmetric.

Conclusions

A technique is developed for estimating R factors using a reservoir engineering constraint. This provides a way of defining the uncertainty in the R factor, given a range of mechanical properties for the field of interest. Based on the mechanical stratigraphy in our field case, R may lie in the range 22 to 7. Application to selected regions of our field with predominantly expansion or compression in the overburden provides a measure of the R factor asymmetry and confirms that R^+ is greater than R^- , in agreement with both previous laboratory and seismic data analyses.

Acknowledgements

The authors thank the sponsors of the Edinburgh Time-Lapse Project Phase V and VI (BG, BP, CGG, Chevron, ConocoPhillips, ENI, ExxonMobil, Hess, Ikon Science, Landmark, Maersk, Nexen, Norsar, Petoro, Petrobras, RSI, Shell, Statoil, Suncor, Taqa, TGS and Total) for supporting this research.

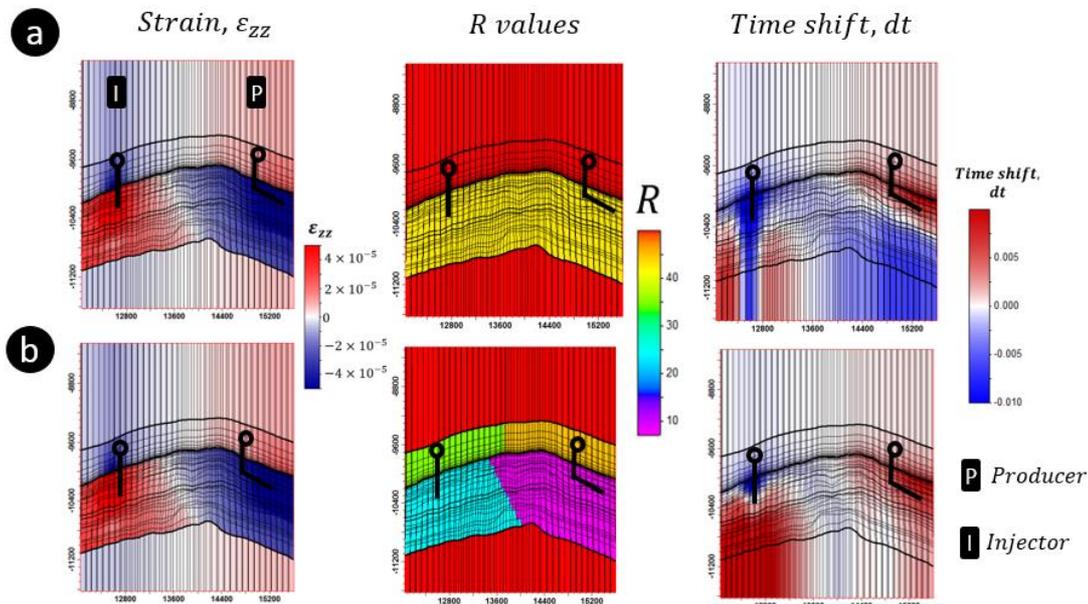


Figure 3 Cross sections showing the modelling of time shift from vertical strain extracted from a synthetic geomechanical model using (a) $R+ = R-$ and (b) $R+ = 3R-$.

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