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A Semi-Empirical Model for Interpreting Rock Strain Sensitivity in 4D Seismic Data

C. MacBeth* (Heriot-Watt University), A. Kudarova (Shell Global Solutions International), P.J. Hatchell (Shell International Exploration and Production), J. Brain (Shell UK Limited)

Summary

Several models have been recently proposed to connect observations of velocity change with strain deformation in and around reservoirs undergoing production and recovery. In this work we show that a simple compliance-based model combined with the original conceptual understanding of Hatchell and Bourne (2005) can adequately explain the magnitude of R factor values currently observed from calibrated field data in a variety of settings. The model is also used to determine an expression for the gradient of overburden time-shift variation with incidence angle. This gradient is predicted to be low but may vary according to the ratio of tangential to normal compliance at the intergranular contacts. This factor could perhaps be used as an additional parameter to assess the post-production state of the overburden.

Introduction

Production and recovery naturally generates strain deformations in both the reservoir and the surrounding rocks, and these may over time manifest as a visible surface subsidence. The geomechanical model forms an essential tool for understanding and mitigating the risks posed by these deformations when strains are detrimental to reservoir management. Time-shifts measured from 4D seismic surveys are a primary source of indirect spatial information on these geomechanical effects, and are of importance when helping to constrain the sub-surface model. The magnitude and offset-dependence of these time-shifts is of current widespread interest.

For post-stack data, the vertical time-shift written in terms of two-way time *t* is given by

$$\Delta t = \int_0^T \left(\varepsilon_{zz} - \frac{\Delta V}{V} \right) dt \qquad (1)$$

where ΔV is the change in vertical velocity V. Key to using this relation is a physical model that links the velocity perturbations $\Delta V/V$ to the vertical strain ε_{zz}. This is required when modelling time-shifts from the strains output by geomechanical simulation or for converting the time-shifts measured from the seismic data to strains to provide the required constraint for geomechanical modelling. For this, the empirical relation proposed simultaneously by both Hatchell and Bourne (2005) and Røste et al. (2005) is widely used

$$\left(\frac{\Delta V}{V} \right)_0 = -R\varepsilon_{ZZ} . \qquad (2)$$

R-values for the Røste-Hatchell-Bourne (*RHB*) model are now available for a range of fields (Table 1), both for the compacting reservoir R^-_{RES} and the overburden in extension R^+_{OB}. Those values for which we have the highest confidence are calculated from well-determined subsurface strain data and highly repeatable time-lapse seismic data. The data indicate R^+_{OB} values lie between 5 and 20, whilst R^-_{RES} values are typically a factor of 5 lower. There are the occasional outliers with R^+_{OB} as high as 100, in addition to an unexplained R^+_{OB} of -1. In the laboratory, *R* factors are found to be sensitive to initial stress state, stress path, and lithology and to a less degree the fluids (for example, Holt et al. 2008). Values tend to be larger than field observations if core samples contain internal microfractures. The condition $R^+ > R^-$ is clearly observed, regardless of lithology. Theory explains $R^+_{OB} > R^-_{RES}$ as the difference in stress/strain states of the reservoir and overburden (Sayers 2006; Herwanger 2008).

Whilst the *RHB* model appears robust and capable of predicting the majority of our observations to date, there are a number of criticisms that have emerged:

(a) There is, as yet, no acceptable underlying model to explain the origin of the *R* factor
(b) Accurate values of $R^-_{RES}, R^-_{OB}, R^+_{RES}, R^+_{OB}$ are still not known and cannot be estimated
(c) The general applicability of the *RHB* model beyond vertical wave propagation is still under discussion (see the comments below);
(d) The *RHB* model uses only vertical strain and not the full strain tensor

In this study we address issues (a) to (d) using concepts closely aligned with the original *RHB* model.

Coupling velocity change to strain

Key to our model is an understanding of how sedimentary rocks behave under stress. At the depths relevant to most production activities, the grains are relatively incompressible and strongly resistant to deformation, whilst the cements and clays are variable in weakness. As a rock is compressed it

Field	R factor values		Subsidence measured?	In situ measurements?	Reservoir Lithology	Reference	Comments
	R+ (OB)	R- (RES)					
Valhall	4 to 9	< 2	Yes	Yes	Chalk	Hatchell et al. 2005 EAGE Conference C012	
Ekofisk	4 to 10	2	Yes	Yes	Overburden & chalk reservoir	Janssen et al. (2006) SEG Conference	Streamer data
Ekofisk	25	16	No	No	Chalk	Wong et al. (2016) EAGE Conference	LoFS
Dan	4 to 6		Yes	No	Chalk	Hatchell et al. (2007) SEG Conference 2867	
Holstein	5 to 10	< 1	No	No	Clastics	Ebaid et al. (2009) SEG Conference 3810	Compressibilities
Malaysia		-1.5 to 0.5	No	No	Carbonate	Private communication	
Shearwater	4 to 6	1 to 3	Yes	No	HPHT Clastics	Bergen et al. (2013) SPE 166574	At platform
Mars	4 to 8	< 2	Yes	Yes	Clastics	Hatchell and Bourne (2005) TLE 24, 1222	
Shearwater	20 to 35		No	No	HPHT Clastics	Staples et al. (2007) TLE 26, 636	OB Chalk group
Elgin-Franklin	7		No	No	HPHT Clastics	Hawkins et al. (2007) First Break, 26, 81	
Elgin-Franklin	20 to 100		No	No	HPHT Clastics	De Gennaro et al. (2008) First Break 26	OB Chalk group
Snorre	20		No	No	Unconsolidated sands	Røste et al. (2015) TLE Nov Issue 1366	
Genesis	5		No	No	Unconsolidated sands	Hodgson et al. (2007) TLE 26, 649	

Table 1 *R values for a range of fields estimated from observed 4D seismic data. References are abbreviated for the sake of brevity.*

initially responds elastically to small strains via pore volume decrease and contacts stiffening. However as strains increase it fails at the grain-grain contacts, and at higher loads due to sliding, rotation and breakage of grains. It has been suggested that the elastic limit for the compaction may be as small as a few millistrains (Jones et al. 1992), similar to those strains encountered in the inter-well space during production. For reservoir compaction, the general velocity change is given by

$$\Delta V_{res} = [\Delta V_{pv}]\uparrow + [\Delta V_{cs}]\uparrow + [\Delta V_{cw}]\downarrow \tag{3}$$

where ΔV_{pv} is the increase ($\uparrow$) due to the pore volume reduction, ΔV_{cs} the increase due to contact stiffening, and ΔV_{cw} a decrease ($\downarrow$) from contact damage. The balance of these contributions depends on the rate of depletion, the lithology and the degree of overpressure and initial stress state. For overburden extension, pore volume increases may be small except in regions where net volumetric strain is significant. Failure of inter-granular bonds is expected to be the dominant mechanism as rocks are known to be an order of magnitude weaker in extension than compression (Holt and Stenebråten 2013). In the case of extension, the velocity change is given by

$$\Delta V_{ob} = [\Delta V_{pv}]\downarrow + [\Delta V_{cw}]\downarrow \tag{4}$$

where ΔV_{cw} now refers to contact detachment, and ΔV_{pv} the decrease due to pore volume inflation. Here, the velocity changes act together to enhance the response. To evaluate the individual mechanisms for any given strain change, we follow Hatchell and Bourne (2005) and determine the relationship to the overall strain. Thus the relevant R factor, R_{pv} can be readily calculated from a known velocity-porosity relation and is calculated to lie in the range 1 to 3. For inter-granular weakening/strengthening the excess compliance approach described by Sayers (2006) is used to determine the velocity change, representing the contact effects by dilute concentrations of aligned compliant elements. A horizontal distribution is considered by Hatchell and Bourne (2005) for the overburden to explain $R^{+}_{OB} > R^{-}_{RES}$. Thus, rocks in their post-production state are transversely isotropic with a vertical axis of symmetry. A calculation from Sayers and Kachanov (1995) gives the desired fractional change of vertical velocity as $\Delta V/V \approx -\delta_N/2$. By simulating inter-granular effects by N self-similar compliant elements per unit volume, we write $\delta_N \cong N\pi a^2(\lambda+2\mu)B_N$, where B_N is the normal compliance and a the circular cross-sectional radius of each element. Scaling the overall porosity change in proportion to the overall strain, we observe that for oblate ellipsoidal shaped elements the R factor $R_c=A/\alpha$ where A depends on the elastic properties and α is the aspect ratio of the elements. R_c = 5 to 20 for a 25% porosity and α = 0.02 to 0.08. For a strain of 10^{-3}, pore volume changes give a $\Delta V/V$ of 0.2% whereas contact stiffening/weakening gives 4%. The unknown in processes (3) and (4) is the amount of strain taken up by the contact stiffening/weakening mechanisms versus pore volume. Finally, (3) also shows that there is the potential for a low or negative R factor.

Offset-dependent time-shifts

Time-shifts with offset/angle are of growing interest as high quality acquisitions are now available with sufficient offset coverage to measure the variations. There is therefore the possibility of using these as additional source of information, as Landrø and Stammeijer (2004) show

$$\Delta t = \int_0^T \left(\varepsilon_{zz} - (1+\tan^2(\theta))\frac{\Delta V}{V} \right) dt. \tag{5}$$

Observations of time-shifts with offset/angle have been published by only a small number of authors. For example, Herwanger et al. (2007) measure time-shifts on the compacting chalk of the South Arne field, and conclude that they decrease with angle. Hawkins (2008) measured an increase with offset in the HPHT Elgin field. Røste et al. (2007) measure time-shifts in PRM and towed streamer data for the compacting chalk of the Valhall field using 2D lines, finding a non-monotonic time-shift variation related to localised stress changes due to a slipping fault. Recently, Kudarova et al. (2016) presented examples from the Mars field (Gulf of Mexico) and HPHT Shearwater field (North Sea) (see Figure 1). They did not observe a strong variation of time-shifts with offset. Additionally, no clear azimuthal dependence has been reported from OBN analysis to date**.** Offset/angle dependence can be calculated for an overburden with horizontally aligned weaknesses as in the previous section. Employing Thomsen (1986) for weak *VTI* anisotropy we find the velocity change should be replaced by

$$\left(\frac{\Delta V}{V}\right)_\theta = \left(\frac{\Delta V}{V}\right)_0 \left(1 - 4g(1-g)\sin^2\theta - 4g^2(1-B_T/B_N)\sin^2\theta\cos^2\theta\right) \tag{6}$$

where $g = (V_S/V_P)^2$. This predicts that velocity change decreases with incidence angle and scales with the R-factor as given previously, thus the time-shift gradient is reduced from the original isotropic prediction in (6). Importantly, most of the time-shift gradient is fixed by g, but it is also impacted to some degree by B_T/B_N. This factor is recognized as relating to the nature and geometry of the internal rock damage (see for example, MacBeth and Schuett 2007). Many previous laboratory studies have concluded that $B_T/B_N < 1$ (e.g. Angus et al. 2009), and hence this second term may also be negative.

Conclusions

We show that a simple compliance-based model combined with the original conceptual model of Hatchell and Bourne (2005) can adequately explain the origins of the R factors as an isotropic elastic compressibility of the pore volume and horizontal planes of contact weakness (stiffness) in the reservoir and overburden. This model can also be used to calculate an expression for the gradient of time-shift with incidence angle, which although quite small is dependent on the mean ratio of tangential to normal compliance representing the loss of intergranular coupling. If estimated, this ratio can perhaps be used as an additional parameter to assess the post-production state of the overburden. Whilst R remains the over-riding parameter that is measured from 4D seismic data, B_T/B_N is a subtler parameter that may also prove of value.

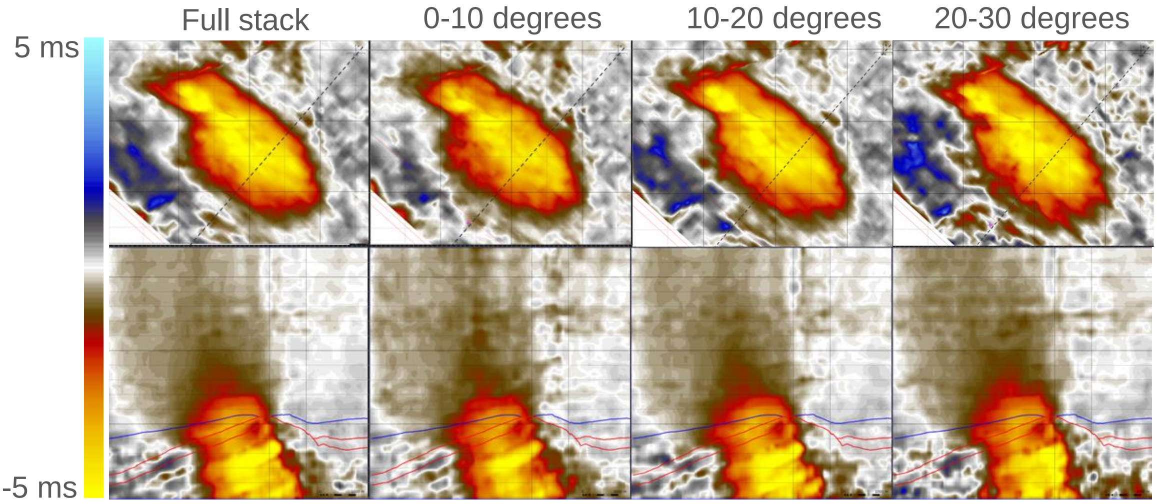

Figure 1 *Observed time-shifts from a North Sea field. Upper panel – map for top reservoir; lower panel – vertical cross-section through the reservoir area. (After Kudarova et al. 2016).*

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