

Compaction of North-sea chalk by pore-failure and pressure solution in a producing reservoir: Supplementary material

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APPENDIX A: ELASTIC MODELING OF CHALK COMPACTION

In order to calculate the elastic contribution to the subsidence we used Segall (1992)'s approach to calculate displacement at the seabed. He used the theory of poroelastacity with the fundamental law that for an isotropic medium the volume strain is related to changes in mean stress and pressure:

$$\varepsilon_{kk} = \frac{\sigma_{kk}}{3K} + \frac{\alpha P}{K} \tag{1}$$

where ε_{kk} is the volumetric strain, σ_{kk} is the mean stress, K is the bulk modulus of the dry rock, P is the pressure, α is the Biot's coefficient. Considering an axisymmetric reservoir the displacement at any point can be expressed by

$$u_z(r,z) = \frac{\alpha}{G} \int_0^\infty \int_0^\infty P(\varrho,d) \cdot g_z(r,z;\varrho,d) \mathrm{d}\varrho \mathrm{d}d$$
(2)

where u_z is the vertical displacement, G is the shear modulus of the reservoir rock, $P(\rho, d)$ is the pressure distribution in radial (ρ) and vertical coordinates (d) and $g_z(r, z, \rho, d)$ is a Green's function at coordinates (r, z). The Green's function at the top boundary - which is the seafloor in our specific case - is

$$g_z(r, z = 0) = -(1 - 2\nu)\rho \int_0^\infty k J_0(kr) J_0(k\rho) e^{-kd} dk$$
(3)

where ν is the Poisson's ration and J_0 is the zero-order Bessel function of the first kind. Equation 3 can be further simplified to

$$g_z(r, z=0) = -(1-2\nu)\varrho \frac{d\kappa^3 E(\kappa)}{4\pi (1-\kappa^2)(\varrho r)^{3/2}}$$
(4)

where $\kappa^2 = 4r\rho/[(\rho + r)^2 + d^2]$ and $E(\kappa)$ denotes the complete elliptical integral of the second kind. Concluding, the upper equations the displacement at the seabed can be expressed as:

Table	1.Mate	erial parameters	for	estimation	of	elastic	parameters
Parameter	Notation	Relevant values	U	sed value	Source		
Biot-coefficient	α	0.7-1		1	Alam et al.	(2012); Warpin	nski and Teufel (1992)
Pressure drop	ΔP	0-21 MPa = 0 - 3000 psi	25 MF	Pa = 3600 psi		Rhett (1	998)
Poisson's ratio	ν	0.15 - 0.25		0.15		Hickman ((2004)
Shear modulus	G	0.4 - 10 GP a	(0.4 GPa		Hickman ((2004)
Pressure drop radius	R	3.4 - 4.2 km		5 km	S	ulak and Danie	elsen (1989)
Depth	h	pprox 3 km		3 km	S	ulak and Danie	elsen (1989)
Thickness	H	150 - 300 m		300 m	S	ulak and Danie	elsen (1989)

$$u_z(r, z = 0) =$$

$$= -\frac{\alpha}{G} \int_0^\infty \int_0^\infty P(\varrho, d) \cdot (1 - 2\nu) \varrho \frac{d\kappa^3 E(\kappa)}{4\pi (1 - \kappa^2) (\varrho r)^{3/2}} d\varrho dd$$
(5)

To prove that elastic contribution is small we simplify Equation 5 by overestimating their components. Therefore, instead of calculating the pressure distribution inside the reservoir through time and space we assume that pressure change is uniform throughout the reservoir and equals to the maximum pressure change observed at Ekofisk (ΔP) and assuming that the reservoir layer is thin enough we get:

$$u_z(r, z=0) = -\frac{\alpha}{G} \Delta P(1-2\nu) R^2 H \frac{hQ^3 E(Q)}{4\pi (1-\kappa^2)(\varrho R)^{3/2}}$$
(6)

where $Q = (4r\varrho/((R+r)^2 + h^2))^{1/2}$.

Using parameters relevant to Ekofisk field (see Table 1) the resulting subsidence can be seen on Figure 1. This shows that the elastic contribution even with overestimation is less than 0.7 meter which is much smaller than the observed subsidence.

APPENDIX B: PREVIOUS MODELS OF EKOFISK SUBSIDENCE

The first models of reservoir chalk compaction was inspired by Johnson and Rhett (1986). They made uniaxial and hydrostatic compaction tests on several chalk samples and found that irrespectively to the initial porosity all samples showed similar compaction pattern: slow compaction at lower stresses which turns into a rapid compaction at certain stress levels depending on the initial porosity of the sample. They plotted a single trend-line on the confining stress-porosity plot representing the rapid compaction of all samples. Their concept was that at lower stresses the compaction is linear until the trend-line is reached and then samples compact following the trend-line throughout the higher stress regime. They identified the linear part of the compaction as elastic and the trend line as plastic pore collapse deformation.

The idea of Johnson and Rhett (1986) was incorporated into several reservoir scale compaction simulations (Boade et al. (1989); Sulak et al. (1991); Johnson et al. (1988)). These models were very accurate in estimating previous compaction but failed to predict reservoir behavior for the future when reservoir was repressurized by saline water injection.

Inspired by the discrepancies of the previous models Chin et al. (1993) introduced the idea that shear failure of the chalk is the main driving mechanism of chalk compaction. Their assumption was based on the observation that stress path was measured low in Ekofisk chalk. This might have caused horizontal effective stress buildup and consequent shear failure. Several reservoir scale models were created based



Figure 1. Estimated subsidence during the first period of the production. Estimation based on pressure history calculations in Section 3.3 and on data from Doornhof et al. (2006). Predictions of the poroelastic model of Segall (1992) is also plotted.

on this idea (e.g. Chin et al. (1994)). Although this approach was able to predict the ongoing subsidence of the Ekofisk field the concept had two discrepancies: it contradicted material parameter measurements which predicted considerably larger stress path than those calculated from in situ measurements and it did not give thorough explanation how horizontal stress can build up.

Shao and Henry (1991) created a unified constitutive chalk rheology model by including both shear failure and pore collapse mechanism. Shear failure was represented by a Lade-Duncan failure criterion, while pore collapse was described by an empirical plastic yield surface which corresponded to an associated plastic flow and the mechanism initiated at a defined main stress.

Later, several other constitutive models were created. Almost all models (except Papamichos et al. (1997)) included 2-3 failure/yield mechanisms which they represented as separate failure surfaces intersecting each other.

The model of Abdulraheem et al. (1994) was used also to predict reservoir compaction. They used the modified Cam-Clay model as yielding surface with a straight line for shear failure and an elliptical cap for plastic pore collapse. They introduced isotropic hardening in case of pore collapse mechanism.

Initially, it was assumed that increasing water saturation has no considerable effect on chalk and therefore increasing pore pressure with water injection would stop subsidence (Johnson et al. (1988)). However, subsidence continued with water injection with similar compaction rates than pre-water injection. The discrepancies from the model was explained by the water weakening of chalk - the loss of mechanical strength of the rock when it becomes water-saturated (e.g. Andersen et al. (1992a,b); Rhett (1998); Sylte et al. (1999)). This appeared to be confirmed by the observation that compaction occurs at a very narrow depth interval inside the reservoir which they identified as the water-oil boundary (Nagel (2001)).

Plischke (1994) listed several explanation for the ongoing compaction as the thermal effect of cold injected water, the time-dependent nature of pore collapse mechanism, and the possible interaction of chalk with water. They created similar failure surfaces as Abdulraheem et al. (1994) and included water weakening effect by introducing a similar but smaller failure surface for water-wetted chalk.

Papamichos et al. (1997) used a generalized Mohr-Coloumb criterion in which they also included the plastic pore collapse mechanism obtaining a continuous enclosed surface as failure surface. The effect of water weakening was incorporated as changes in capillary pressure. They assumed that strain is dependent on water saturation by using the following equation of state:

$$\dot{\sigma}'_{ij} = C^{ep}_{ijkl} \dot{\varepsilon}_{kl} + P_{ij} \dot{S}_w, \tag{7}$$

where σ'_{ij} is the effective stress tensor, C^{ep}_{ijkl} is an elastoplastic compliance matrix, S_w is the water saturation and denotes time-derivatives and

$$P_{ij} = \frac{\mathrm{d}(S_w \cdot p_{cp})}{\mathrm{d}S_w} \delta_{ij} + D_{ij}^{ep},\tag{8}$$

where p_{cp} is the capillary pressure and D_{ij}^{ep} is an elastoplastic saturation matrix.

Rhett (1998) created a reservoir scale simulation for chalk compaction. He described compaction as elastic before water injection and plastic after water-injection and introduced two empirical laws of compaction for each case. Both laws related porosity and pore pressure to strain. The assumption that pre-water injection compaction was elastic still holds in reservoir modeling of North Sea chalks (e.g. Kristiansen et al. (2010)) even it violates simple physical considerations (see Appendix A). Du and Olson (2001) proposed a poroelastic compaction model for Ekofisk based on the work of Segall (1992) but concrete calculations have never been done.

A different approach for water weakening was introduced by Datcheva et al. (2001), De Gennaro et al. (2003) and Collin et al. (2002). They had the assumption that strain is composed of two terms: a mechanical term and a term related to capillary effects both having elastic and plastic component:

$$\dot{\varepsilon} = \dot{\varepsilon}_{m,e} + \dot{\varepsilon}_{m,p} + \dot{\varepsilon}_{s,e} + \dot{\varepsilon}_{s,p},\tag{9}$$

where e in subscript denotes: elastic, p stands for plastic, m for mechanical and s for capillary effects. They argued that increasing water saturation decreases pre-consolidation pressure, increases cohesion while traction strength and the friction angle are not changed and that 'suction' (the difference of partial pressure of oil and water) above a threshold level creates plastic strain.

The time-dependent nature of chalk compaction was early identified (e.g. Johnson and Rhett (1986); Johnson et al. (1988)). They discovered that if compaction tests are performed slowly the ultimate strain is higher than if it were performed fast. They also quantified the time-dependence by measuring compaction in case of constant stress for a longer time and plotting the inverse volume against inverse time meaning that the time-dependence of strain is:

$$\varepsilon = \frac{t}{c_1 + c_2 \cdot t} \tag{10}$$

where c_1 and c_2 are constants. If extrapolated to infinite time an ultimate strain can be obtained corresponding to any effective stress value. Some reservoir models (e.g. Andersen et al. (1992a)) used the ultimate strains to calculate subsidence.



Figure 2. Time-dependence of strain during creep: data from a sample creep experiment (M13 from Zhang et al. (2010)) fitted with the different model of time-dependence. With the right fitting parameters all the models fit the curve sufficiently well.

For comparison Hellmann et al. (2002) found in their experiment of chalk compaction (from Paris basin) that $\dot{\varepsilon} \propto \varepsilon^{\dot{c}}$, where *c* varied between -2 and -5. This result can be transformed into:

$$\varepsilon \propto t^c$$
 where $c \in [1/6, 1/3]$. (11)

Zhang et al. (2010) performed experiments on different calcite samples and found that on CaCO₂ solution samples strain rate were slower than rates predicted by a model of $\varepsilon \propto t^{1/2}$. Oil saturated and dry samples did not show time-dependent compaction. On Figure 2 a sample dataset from Zhang et al. (2010) is plotted with the previous time-dependence relations. With the right fitting parameters these models give similar results to predict strain as function of time.

While the existence of time-dependent creep of chalk was well-known, very few constitutive models and none of the reservoir scale models included the phenomenon. Datcheva et al. (2001) refined the initial concept described in Equation 9 and used viscoplastic strain rates instead of plastic strain rates. Their main concept was that viscoplastic strain rate depends on the 'age' of the material which in turns depends on the viscoplastic strain previously accumulated.

While the mentioned models became more and more sophisticated to describe chalk behavior and to predict previous Ekofisk compaction, all of them attempted to fit or modify a general rheology model instead of describing the underlying physical phenomena of the chalk compaction.

Japsen et al. (2011) showed non-linear variations in chalk rheology in geological time-scale and explained as triggered by the collapse of the largest pores and a decrease in the effects of inhibition by organic compounds associated with the chalk that hinders carbonate dissolution at low effective stresses. If directly applied to the Ekofisk field it would result in a total seafloor subsidence of 60-90 m.

APPENDIX C: MODEL EQUATIONS

The governing equation of the compaction model is:

$$\dot{\varepsilon}_{v}(t) = \frac{1}{V_{0}} \frac{\partial V}{\partial t} = S_{w} \cdot \rho_{f}\left(\sigma_{e}, p(r)\right) \dot{\xi}\left(\sigma_{e}, \Phi_{0}, T\right)$$
(12)

where microscopic fracture density ρ_f and pressure solution rate $\dot{\xi}$ are calculated independently and water saturation S_w has a constant value. Fracture density is the expected value of fractures cut by a vertical line with unit length. Fractures are initiated from pores with characteristic radius larger than a threshold r_{max} obtained from the relation:

$$r_{max}^{1/2} \sigma_e^2 = \sqrt{\gamma E} = \sqrt{12.9 \text{ GPa} \cdot 0.32 \text{ Jm}^{-2}} = 64.25 \text{ MPa} \cdot \mu \text{m}^{1/2}$$
 (13)

where γ is the interfacial energy of dry calcite and E is the Young's modulus of calcite. The number of fractures is therefore proportional to the number of the pores involved in the fracturing process and this can be obtained by dividing the volume of these pores by the volume of unit cube and the average pore thickness d which is the first momentum of the pore size distribution. Assuming a Weibull-type pore radius distribution p(r) and a corresponding volumetric pore size distribution P(V) with a shape factor of 1.5 and a mean pore size of 2.2 μ m, it can be calculated as:

$$\rho_f = \frac{\Phi}{d} \int_{V(r_{max})}^{\infty} p(V) dV = \frac{\Phi}{d} \int_{V(r_{max})}^{\infty} 0.3535 \ \mu \text{m}^{-7/6} \frac{\sqrt[6]{r/(1-g)}}{\sqrt{1.5}^3} \cdot e^{-(0.7071 \ \mu \text{m}^{-1/2} \sqrt{r/(1-g)}/1.5)} dr$$
(14)

where r is in micrometer, g is the characteristic flattening of the pores (if they are assumed to be ellipsoidal), the numerical constants inside the integral are describing the volumetric distribution corresponding to the Weibull-distribution p(r) with a shape factor of 1.5 and a mean pore size of 2.2 μ m (Weibull (1951)), and $V(r_{max})$ is the volume of a pore with radius r_{max} for the calculations it is assumed to be:

$$V(r) = \frac{4}{3}r^3(1-g)^2\pi.$$
(15)

We use two different approaches to calculate the pressure solution rate ξ . In the first case it is treated as constant calculated from Zhang et al. (2010)'s experiments:

$$\dot{\xi}_1 = 1.2 \cdot 10^{-13} \,\frac{\mathrm{m}}{\mathrm{s}}.$$
 (16)

In the second case we use a theoretical model based on Pluymakers and Spiers (2014) assuming a cubic packing of spherical grains where the pressure solution is limited by the diffusion of material from the grain contacts towards the unstressed surface of the grains. In this case pressure solution rate is calculated as:

$$\dot{\xi}_2 = \frac{2\pi \cdot A_c DCSZ}{\zeta F d^2} \left[exp\left(\frac{\sigma_e \Omega}{RT} \frac{Z}{F} \frac{q}{q-2\phi}\right) - 1 \right] \left(\frac{q}{q-2\phi}\right)$$
(17)

where $q = 2(1 - \pi/6) = 0.9528$ and the diffusion constant D is calculated as:

$$D = D_0 exp\left(\frac{Q_d}{RT}\right) \quad \text{where} \quad D = 10^{-10} \ \frac{\mathrm{m}^2}{\mathrm{s}} \text{ at } T = 25^{\circ}C, \tag{18}$$

the average solubility C of calcite in the grain boundary fluid (a dimensionless number) has the temperature dependence:

$$log(C^{2}) = -171.9065 - 0.077993 \frac{1}{K}T + \frac{2839.319K}{T} + 71.595log(T)$$
(19)

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Tab	ole	2.	Internal pa	arameters	used	in	the	pressure	solution	model
-	Symbo	1	Definition	U	sed value			Source		_
_	A_c		Geometric constant		4		Pluy	nakers and Spi	ers (2014)	=
_	S		Grain boundary thickne	SS	10 ⁻⁹ m			Zhang et al. (2	010)	_
_	Z		Coordination number		4		Pluy	nakers and Spi	ers (2014)	_
	ζ		Geometric factor		0.5		Pluy	nakers and Spi	ers (2014)	_
_	F		Grain shape factor		π		Pluy	nakers and Spi	ers (2014)	_
_	d		Diffusion distance		$4.4 \ \mu \mathrm{m}$	1	Taken equ	al to the averag	e pore diameter	,
	Ω		Molar volume of calcit	e 3.692 ·	$10^{-5} \text{ m}^3/\text{i}$	mol		Zhang et al. (2	010)	
_	R		Universal gas constant	t 8.314 J	$\cdot \operatorname{mol}^{-1} \cdot \mathbf{k}$	X^{-1}				
_	Φ		Porosity		0.35		Sula	ak and Danielse	en (1989)	_
	Q_d		Activation energy	3300	$0 \text{ J} \cdot \text{mol}^{-1}$	1		Zhang et al. (2	010)	

where temperature is given in kelvin. Other parameters are constant and shown in Table 2. Equation 17 can be simplified to:

$$\dot{\xi}_d = MDCS \frac{1}{d^2} \left[exp\left(\frac{\sigma_e \Omega}{RT} f(\phi)\right) - 1 \right] f(\phi)$$
(20)

where $M = A_c Z \exp(Zq/\pi)/(\zeta F) = 34.27$ is a constant and $f(\phi) = 1/(q-2)\phi$.

APPENDIX D: DERIVATION OF THE PRESSURE PROPAGATION EQUATIONS

The equations of pressure propagation (Equation 7 and 8 in Section 3.2) can be combined into:

$$\nabla \left[\rho \nabla \frac{k}{\mu} P \right] = -\frac{\partial (\Phi \rho)}{\partial t}.$$
(21)

If we assume that k and μ are constants we get:

$$\nabla \left[\rho \nabla P\right] = -\frac{\mu}{k} \frac{\partial (\Phi \rho)}{\partial t}.$$
(22)

Using the compressibility relation of the reservoir fluid $\rho = \rho_0 \cdot exp(\beta P)$ this can be further simplified to:

$$\nabla^2 \rho = -\frac{\mu\beta}{k} \frac{\partial(\Phi\rho)}{\partial t}.$$
(23)

Assuming a linear porosity change the right term of the equation can be written as:

$$\frac{\partial(\Phi\rho)}{\partial t} = \rho \frac{\partial\Phi}{\partial t} + \Phi \frac{\partial\rho}{\partial t}$$
(24)

and using

$$\frac{\partial \Phi}{\partial t} = \frac{\partial \Phi}{\partial P} \frac{\partial P}{\partial \rho} \frac{\partial \rho}{\partial t}$$
(25)

and

$$\frac{\partial P}{\partial \rho} = \frac{1}{\beta \rho} \tag{26}$$

Frontiers

7

Keszthelyi et al.

we can obtain

$$\nabla^2 \rho = -\frac{\mu \Phi}{k} \left(\beta + \frac{1}{\Phi} \frac{\partial \Phi}{\partial P}\right) \frac{\partial(\rho)}{\partial t}.$$
(27)

Introducing $\kappa = \mu \Phi / k \cdot (\beta + (1/\Phi)(\partial \Phi) / (\partial P))$ and cylindrical coordinates this can be rewritten to:

$$\kappa \left\{ \frac{\partial^2 \rho}{\partial r^2} + \frac{1}{r} \frac{\partial \rho}{\partial r} \right\} = \frac{\partial \rho}{\partial t}$$
(28)

The boundary conditions can be written as:

$$\rho(r) = \rho_0 \qquad \text{at} \quad t = 0 \tag{29}$$

 $\rho(r_2) = \rho_0$ at t > 0 (30)

$$\rho(r_w) = \rho_0 e^{\beta(p_w - p_0)} \quad \text{at} \quad t > 0$$
(31)

With these boundary conditions Equation 28 will have the following solution:

$$\rho = \underbrace{\frac{\rho_0 \ln \frac{r}{r_w} + \rho_w \ln \frac{r_2}{r}}{\ln \frac{r_2}{r_w}}}_{\text{stationary}} + \underbrace{\pi \left(\rho_0 - \rho_w\right) T\left(r_w, r_2, r\right)}_{\text{space dependent}} \cdot \underbrace{e^{-\kappa \alpha_n^2 t}}_{\text{time-dependent}}$$
(32)

where $T(r, r_w, r_2)$ is a complex function describing the fluid density as a function of radius and r_w , r_2 boundary conditions. Eq. 32 shows that to investigate the time-dependent evolution of fluid density and in turn pore pressure, it is enough to consider the exponential component of the equation.

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