Comments	Initial stress state		
	Top Vlielar	1785 m	
	Overburden pressure using an equivalent rock density of 2500 kg/m3		
Calculated	Sv	43,78 Mpa	Vertical stress
Calculated	Sh	27,60 Mpa	Minimum horizontal stress (assumed as estimated fracturing pressure of Vlieland Claystone) most likely should be higher
Assumed	SH	43,78 Mpa	Maximum horizontal stress
Input	Pp	20,30 Mpa	Pore pressure initial pressure in gas zone
Calculated	**σeff**	**18,08475** Mpa	
Calculated	Sh/Sh	0,630	Ratio min to max horizontal stress
Check		0.55 - 0.88	Ratio min to max horizontal stress from the Hoeve project
	Stress state after depletion		
	Overburden pressure using an equivalent rock density of 2500 kg/m3		
Calculated	Sv	43,78 Mpa	Vertical stress
Calculated	Sh	27,60 Mpa	Minimum horizontal stress (assumed as estimated fracturing pressure of Vlieland Claystone)
Assumed	SH	43,78 Mpa	Maximum horizontal stress
Input	Pp	2,50 Mpa	Pore pressure initial pressure in gas zone
Calculated	**σeff**	**35,88475** Mpa	
Calculated	Sh/Sh	0,630466	Ratio min to max horizontal stress
Check		0.55 - 0.88	Ratio min to max horizontal stress from DeHoeve project
Equation 1	K	=E/(3*(1-2v))	Bulk modulus
Input from Table 4.2	Ec	7000 Mpa	Vlieland claystone Young's modulus
Input from Table 4.2	Es	20000 Mpa	Vlieland sandstone Young's modulus
Input from Table 4.2	vc	0,2	Vlieland claystone Poisson's ratio
Input from Table 4.2	vs	0,17	Vlieland sandstone Poisson's ratio
Calculated using Eq.1	Kc	3889 Mpa	Bulk modulus Vlieland claystone
Calculated using Eq.1	Ks	10101 Mpa	Bulk modulus Vlieland sandstone
Assumed	porosity	8 %	Shale/claystone
Assumed	porosity	0,2 fraction	Sandstone
Input from Table A1	Cc	0,50 Mpa	Unconfined strenght of claystone: source Table A1
Calculated	Cs	69,1 Mpa	Estimated using Plumb correlation - unconfined strenght of sandstone
Input Table A5	βc	0,000012 1/C	Linear thermal exp. Coefficient
Input Table A5	βs	0,000017 1/C	Linear thermal exp. Coefficient
Calculated	αc	0,695	Biot coefficient claystone
Calculated	αs	0,807	Biot coefficient sandstone
	Sandstone stress change per temp		
Input	Treservoir	70 C	
Assumed downhole flowing temp	Tw min do	20 C	
	Stress caused by cold water injection		
	Short time cold water injection		
Calculated	Δσc	-2,6 Mpa	Claystone stress change in cylindrical cooled zone
Calculated	Δσs	-10,2 Mpa	Sandstone stress change in cylindrical cooled zone
	Long time cold water injection		
	Increase in Tensile stress due to the cooling effect		
Calculated	Δσc	-5,25 Mpa	Claystone stress change in cylindrical cooled zone - horizontal stress change
Calculated	Δσs	-20,48193 Mpa	Sandstone stress change in cylindrical cooled zone - horizontal stress change
Calculated	Xc	0,521	Poro elastic constant - Sandstone
Calculated	Xs	0,642	Poro elastic constant - Claystone
	Fracture openning pressure (variation in reservoir pressure)		
Estimated see above	Pf c	27,60 Mpa	no change as no pressure change in claystone formation - cap rock
Calculated	Pf s	16,178 Mpa	depleted sandstone
	Fracture openning pressure (variation in reservoir pressure + cooling effect)		
Calculated	Pf c	22,35 Mpa	
Calculated	Pf s	-4,304 Mpa	
Calculated	Pf s	7,1 Mpa	reservoir pressure back to initial
	Estimated Effective stress Including cooling effect		
	σeffc	16,33475 Mpa	Effective stress claystone - caprock
Depleted	σeffs	29,05744 Mpa	Effective stress sandstone at low pressure
to initial pressure	σeffs	11,25744 Mpa	Effective stress sandstone at elevated pressure
	Fracture opening pressure		
	Pfoc	22,35 Mpa	Claystone - cap rock estimated fracture openning pressure after cooling from 70 to 20 C deg
	Pfos	Mpa	
to initial pressure	Pfos	7,12 Mpa	Sandstone fracture openning pressure - pressure back to initial reservoir pressure
	Rock strenght		
Uniaxial compressive strenght		4,16 Mpa	Claystone
Uniaxial compressive strenght		11,9 Mpa	Sandstone
Tensile strenght		0,42 Mpa	Claystone
Tensile strenght		1,19 Mpa	Sandstone

$$\sigma_T = \frac{E\beta\Delta T}{1-\nu}$$

$$X = \frac{1-2\nu}{1-\nu}\alpha$$

Stress changes within the reservoir can be calculated if the appropriate hydraulic and poroelastic parameters are known.The following equation can be employed to quantify the ratio between thermoelastic (σ T) and poroelastic (σ p) stresses due to injection and production in geothermal reservoirs:

$$\frac{\sigma_T}{\sigma_p} = \frac{3\beta\Delta T}{\alpha\Delta p/K}$$

where α is Biot's coefficient K is the bulk modulus, β is the linear thermal expansion coefficient and are the change in temperature and pressure respectively. Uniaxial deformation assumption (sides and bottom of reservoir constrained) has been one of the most popular approaches to model the geomechanical behaviour of reservoirs. Assuming uniaxial boundary conditions where no horizontal strain occurs the ratio of changes in horizontal stress due to changes in reservoir pressure and temperature can be estimated.

$$\frac{\Delta S_h}{\Delta P} = \frac{1-2\nu}{1-\nu}\alpha$$

where Sh is the minimum horizontal stress, ν is the Poisson's ratio and the right hand side is equal to poroelastic stress coefficient. Thermoelastic stress and strain evolution due to temperature variations in uniaxial boundary conditions can be estimated according to the following equation:

$$\sigma_T = \frac{E\beta\Delta T}{1-\nu}$$

where E is the Young's modulus and Eβ/(1- ν) is the thermoelastic stress coefficient.

$$\varepsilon_v = \frac{1+\nu}{1-\nu}\beta\Delta T$$

An increase in temperature causes an increase in volume and results in compressional thermoelastic stress. A decrease in temperature causes a reduction in volume and results in tensile stresses. Thermoelastic effects predominates in case of increase in rock mechanical stiffness, which could be due to an increase in confining pressure. The Biot effective coefficient is defined as the contribution of pore pressure to the total stress, i.e. the efficiency of pore fluid in counteracting to the total applied stress.

$$\sigma^{eff} = \sigma - \alpha P_p$$

Rock will fail in tensile mode if the minimum effective principal stress becomes tensile and equal to the tensile strength of the rock (Fjaer, Holt, Horsrud, & Raaen 1992):

$$\sigma_3^{eff} = \sigma_3 - \alpha P_p \geq \sigma_{tensile}$$

In situ stress state

The minimum horizontal stress (Sh) magnitude is evaluated by hydraulic fracturing to be > 27.6 MPa. The vertical stress (Sv) was estimated by considering the average weight of the overburden strata and the thickness of the rock units. An equivalent density of 2500 kg/m3 for the entire overburden was calculated.

Consequently, vertical stress is equal to 43.8 MPa at a depth of 1785 meters. The most uncertain component of stress tensor is maximum horizontal stress (SH). Jaeger et al. (2007) derived the ratio between effective principal stresses as a function of sliding friction coefficient, which can be employed to give the bounds on SH. Moeck et al., (2008) employed this approach and stated that the maximum horizontal stress is equal or less than 0.78 Sv in normal faulting regime. In strike slip faulting regime it is equal or less than vertical stress Sv.

Therefore, $\sigma_m^{eff} = \frac{1}{3}(S_V + S_h + S_H) - P_p$ calculated by:

to be 18.08 MPa. The effective Terzaghi stress is defined as Seff= S-Pp, where Pp is pore pressure and S is a component of principal stress tensor.

σ≤αΔεt

MECHANICAL PROPERTIES OF SEDIMENTARY ROCKS

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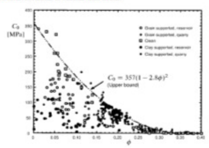


Fig. 3.15. Strength of sandstone. After Plumb (1994). © 1994 Taylor & Francis Group. Used with permission.

Table 4-2. Geomechanical properties of the formations

Stratigraphy	Formation	Depth [m TVD]	Δtc [μsec/ft]	E [GPa]	ν [-]
Upper North Sea group	Quaternary-Miocene	0-500	195	0.40	0.30
Middle North Sea group	Oligocene	500-620	175-215	1.10	0.30
Lower North Sea group	Upper Eocene	620-630	125-200	1.15	0.30
	Bruxellian sand	630-750	115-205	1.20	0.30
	Lower Eocene	750-950	135-165	1.40	0.30
	Paleocene clay	950-1000	135-165	1.50	0.30
Chalk CK	Omeland chalk	1000-1750	55-100	14	0.30
	Texel chalk	1750-1820	60-90	12	0.30
Rijnland group	Holland marl	1820-1860	85-105	10	0.20
	Vlieland claystone	1860-1875	85-120	7	0.20
	Vlieland sandstone		75-85	20	0.17
Zechstein group	Anhydrite	1873-1920	50-65	50	0.28
	Dolomites	1920-1990	50-65	*	0.20
Upper Rotliegend group	Slochteren sandstone	1990-2080	65-95	20	0.20
Basement				22	0.20

* $E = 49.14216 - 0.7906814 \times \phi$

The analysis of the wells located in the area of de Hoeve, presented in chapter 10, shows that none of them can help us evaluate the magnitude and orientation of the stress field. However, stress measurements performed in the frame of the Bergermeer project show that the ratio of the minimum (maximum) horizontal stress to the vertical stress at the depth of the reservoir is 0.55 (0.88).

The orientation of the stress field can be assumed to be the regional trend as given by the World stress map project Figure 4-2, that is NW-SE.

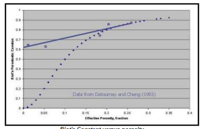
Biot's Constant is the ratio of the volume change of the fluid filled porosity to the volume change of the rock when the fluid is free to move out of the rock (ie. the hydraulic pressure remains unchanged)..

For rock with porosity:
1: ALPHA = 1 - Kb / Km
OR 2: ALPHA = 1 - Cm / Cb

For rock with no porosity, Kb = Km so ALPHA = 0.

If shear travel time is unavailable, this empirical relation may be useful:
3: ALPHA = 1 - (1 - PHID) ^ KS8

where KS8 has the range 2 to 3, with KS8 = 3 most often used.



Biot's Constant versus porosity

In the absence of good shear sonic data, Biot's Constant can be estimated from the graph above, based on known or assumed lithology (courtesy Barree and Associates). This graph suggests KS8 in the previous equation is greater than 2.0. The empirical straight line fit to the data is:
4: ALPHA = 0.62 + 0.935 * PHIe

Rock Specific Heat:

Rock specific heat data was also taken from the literature and was incorporated into the model. The Data was converted to reservoir conditions [17].

Table 3-5 Rock Specific Heat as a function of Temperature

	Temp, °C	Cp Rock, kJ/m³K
Z2C	25	2219
	127	2530
	227	2740
Vlieland	25	2217
	127	2217
	227	2533

Thermal Conductivity

Thermal conductivity plays a less significant role towards the overall heat transfer as the heat transfer is mostly dominated by the heat convection effects in the reservoir.

Overall thermal conductivity was estimated for the Z2C formation based on the rock and fluid properties given in the Prosper Database by assuming an average porosity of 7%. The fluid composition was considered constant at 88% gas and 12% water within the reservoir formation.

$$k_{combined} = (k_{rock} * (1-\varphi)) + (k_{water} * \varphi * S_{wi}) + (k_{gas} * \varphi * (1-S_{wi}))$$

TABLE A.4 Sound velocities for some common rock types

Material	Density ρ 10^3 (kg/m³)	P-wave velocity v_p (km/s)	S-wave velocity v_s (km/s)	Conditions
Sand, dry, loose	1.5–1.7	0.3–1.0	0.05–0.4	dry, from surface to ≈50 m depth
Sand, dry	1.6–1.7	1.0–1.7	0.4–0.9	dry, loaded from ≈1 to ≈50 MPa
Sand, wet, loose	1.8–2.2	1.5–2.0	0.05–0.4	saturated, from surface to ≈50 m depth
Sandstone, competent	2.0–2.65	1.8–4.5	1.0–3.0	dry, various porosities
Berea sandstone	2.2	3.8–4.0	2.3–2.4	brine saturated, confined
Sandstone, weak	1.7–2.0	1.0–2.0	0.6–1.2	dry, various porosities
Red Wildmoor sst.	2.0	1.7–2.0	1.1–1.3	dry, confined
Clay	1.9–2.1	1.5–1.6	0.1–0.3	saturated, from surface to ≈50 m depth
London Clay, deep	2.0	1.7–1.8	0.8–1.1	saturated
Shale	2.3–2.8	1.6–4.5	0.7–3.0	saturated, various porosities
Weak shale, North Sea	1.8–2.3	2.4–2.6	1.2–1.3	saturated, unconfined
Chalk, high porosity	1.4–1.7	1.8–2.6	1.0–1.5	saturated, field and lab. data
Chalk, low porosity	1.7–2.4	2.6–5.0	1.5–3.5	saturated, field and lab. data
Limestone	2.4–2.7	3.5–6.0	2.0–3.5	various
Basalt	2.5–2.9	3.5–5.5	1.7–3.4	dry & saturated; stress 0–100 MPa
Granite	2.6–2.7	5.5–6.5	3.0–3.5	dry; stress 0–100 MPa

TABLE A.5 Thermal properties for some rocks and materials

Material	Linear thermal exp. coeff. 10^6 (K^{-1})	Conditions	Thermal conductivity W m^{-1} K^{-1}	Conditions	Heat capacity J kg^{-1} K^{-1}	Conditions
Berea sst.	13	100–200 °C	2.34	20 °C, dry		
Bandera sst.	20	100–200 °C	1.70	20 °C, dry		
Boise sst.	17	100–200 °C	1.47	20 °C, dry		
Sandstone					824–1000	25 °C, dry
Pierre shale			1.30–1.70	35–75 °C, 1–24 MPa saturated		
Mancos shale	13–20	20–75 °C 0–7 MPa	1.50–2.25	35–80 °C, 1–24 MPa saturated		
Queenston shale	11–13	20–75 °C 0–3.5 MPa	1.74–1.95	35–90 °C, 1–24 MPa saturated		
Quartz ⊥ c*	18	20–100 °C				
∥ c	10	20–100 °C	13	0 °C	735	0 °C
Calcite ⊥ c	24	20–100 °C				
∥ c	−5	20–100 °C				
Aluminium	23.1	25 °C	200	27 °C	900	25 °C
Water	70**	20 °C	0.6	20 °C	4182	20 °C

*Relative to crystallographic axis.
**Computed from volumetric expansion.

TABLE A.3 Density, elastic moduli and sound velocities for some common materials

Material	Density ρ 10^3 (kg/m³)	Bulk modulus K (GPa)	Shear modulus G (GPa)	P-wave velocity v_p (km/s)	S-wave velocity v_s (km/s)
Calcite	2.71	74.0	27.5	6.39	3.18
Quartz (α)	2.65	37.5	41.0	5.90	3.94
Muscovite (mica)	2.79	52–62	31–41	5.78–6.46	3.33–3.84
Biotite	3.05–3.12	41–60	12–42	4.35–6.8	2.00–3.70
Feldspar (average)	2.63	76	26	4.68	2.39
Pyrite	4.93	147.5	132.5	8.10	5.18
Dolomite	2.87	76–95	45–52	6.93–7.34	3.96–4.23
Barite	4.50	53	22	4.29	2.22
Olivine	3.32	130	80	8.54	5.04
Steel	7.9	198–205	57–80	5.9–6.3	2.7–3.2
Aluminium	2.7	77–98	23–26	6.3–7.0	2.9–3.1
Water (fresh)	1.00	2.25		1.50	
Ice	0.9			1.3–1.7	
Crude oil (room temp.)	0.7–1.1	1.2–2.8		1.3–1.7	
Air (atmospheric press.)	$0.14 \cdot 10^{-3}$	$0.15 \cdot 10^{-3}$		0.33	
Plexiglass	1.2			2.55	1.28
Ethanol	0.79	0.89		1.06	

TABLE A.2 Static mechanical properties for some specific rocks

Material	Density ρ 10^3 (kg/m³)	Young's modulus E (GPa)	Poisson's ratio ν	Unconf. compr. strength C_0 (MPa)	Tensile strength T_0 (MPa)
Red Wildmoor⊥	1.9–2.0	1.8		14	0.4–0.7
sandstone∥	1.9–2.0	1.3		7	0.4–0.7
Weak reservoir sandstone (North Sea)	1.9	0.4	0.45	1	
Berea sandstone	2.18	20	0.38	74	
St. Peter sandstone	2.34	4–10	0.05–0.10	37	
Weak shale (North Sea)	2.35	1		6	
Pierre shale I	2.37–2.39	0.77–1.12	0.35–0.37	7.5–13.9	
Shale (El Paso)	2.47	26	0.10	115	
Bedford limestone	2.21	29	0.29	51	1.6
Solenhofen limestone	2.62	64	0.29	245	4.0
Hackensack siltstone	2.59	26	0.22	123	3.0
Nevada Tuff	1.61	5.0	0.21	24	1.4
Rock salt (Diamond crystal)	2.16	5	>0.5	21	0.8
Schist⊥	2.81	21	0.31	55	0.6
(Luther Falls)∥	2.82	58	0.18	83	5.2

⊥Loaded perpendicular to bedding.
∥Loaded parallel to bedding.

TABLE A.1 Static mechanical properties for some common rock types and materials

Material	Density ρ 10^3 (kg/m³)	Young's modulus E (GPa)	Poisson's ratio ν	Unconf. compr. strength C_0 (MPa)	Tensile strength T_0 (MPa)
Unconsolidated sands	1.5–1.7	0.01–0.1	∼0.45		
Sandstone	2.0–2.65	0.1–30	0–0.45	1–250	
Clay	1.9–2.1	0.06–0.15	∼0.40	0.2–0.5	
Shale	2.3–2.8	0.4–70	0–0.30	2–250	
High porosity chalk	1.4–1.7	0.5–5	0.05–0.35	4–15	
Low porosity chalk	1.7–2.0	5–30	0.05–0.30	10–40	
Basalt	2.7–2.9	50–100	0.2–0.3	200–350	10–15
Granite	2.6–2.8	5–85	0.1–0.34	50–350	5–15
Dolomite	2.4–3.2	10–100	0–0.5	40–350	
Limestone	1.4–2.9	2–100	0–0.3	5–250	
Gneiss	2.7–3.1	40–100	0.1–0.3	50–250	
Marble	2.7–3.2	5–90	0–0.3	50–250	
Ice	0.9	8	0.35		
Steel	7.9	200	0.28	220–900*	350–1200

*Yield strength.

Effective pressure