Problem 1

(1 points each) Circle the best answer:

(i) Which of the following conditions is true in a *true triaxial* compression test for principle stresses, S_1, S_2, S_3

(a) $S_1 > S_2 = S_3$

(b) $S_1 < S_2 = S_3$

(c) $S_1 \neq S_2 \neq S_3$

(ii) True or False: It's possible to limit or prevent sand production by changing the azimuth of deviation while drilling a well.

(a) True

(b) False

(iii) In a vertical wellbore, we expect breakouts to occur along the direction of

(a) S_v.

(b) S_{Hmax}.

(c) S_{hmin}.

(iv) True of False: In the Kristonovich-Geertsma-de Klerk (KGD) fracture model the fracture width is considered to be a constant with respect to fracture height at any point along the length of the fracture.

(a) True

(b) False

(v) True or False? The elastic behavior of an *isotropic* solid is fully characterized by two independent constants.

(a) True

(b) False

(vi) True or False? A *stable wellbore* is defined as one that is absent from any breakouts.

(a) True

(b) False

(vii) In a vertical wellbore, we expect drilling induced tensile fractures to occur along the direction of

(a) S_v.

(b) S_{Hmax}.

(c) S_{hmin}.

(viii) True or False? In a lower hemispherical projection plot associated with drilling deviated wells, the outermost concentric ring, i.e. the edge of the plot, represents a horizontal well.

(a) True

(b) False

Problem 1 continued on next page...

(ix) True or False: It's possible to limit or prevent sand production by carefully orienting well casing perforations during completions.

(a) True

(b) False

(x) Which of the following is NOT a type of plate boundary?

(a) Convergent plate boundary

(b) Transform plate boundary

(c) Asthenospheric plate boundary

(xi) *Compaction drive* can occur during reservoir depletion as a result of

(a) Porosity decreasing.

(b) Permeability decreasing.

(c) Fluid viscosity increasing.

(xii) The range of depths for the earth's crust is

(a) 0-5 km.

(b) 0-100 km.

(c) 0-2900 km.

(xiii) So-called *cap failure models* provide the ability to model

(a) inelastic effects occurring for increasing hydrostatic pressure.

(b) failure in pure shear.

(c) inelastic effects due to slip on crystallographic planes.

(xiv) True or False? A typical range for Poisson ratio in rocks is between $0.2 < \nu < 0.6$

(a) True

(b) False

(xv) True or False? The eigenvectors of the stress tensor are the principle stress directions.

(a) True

(b) False

(xvi) True or False? In the Perkins-Kern-Nordgren (PKN) fracture model, the fracture width is assumed to be a fixed height ellipse at any given cross section along the fracture length.

(a) True

(b) False

(xvii) In a normal faulting regime, the hanging wall moves which way relative to the footwall?

(a) Vertically up

(b) Vertically down

(c) Horizontally

Problem 1 continued on next page...

(xviii) In a strike-slip faulting regime, the hanging moves which way relative to the footwall?

(a) Vertically up

(b) Vertically down

(c) Horizontally

(xix) Which of the following *is* a standard assumption of poroelasticity.

(a) There is an interconnected pore system uniformly saturated with fluid.

(b) The pore pressure inside a statistically defined volume of rock is extremely heterogeneous.

(c) The total volume of the pore system is large compared to the volume of the rock.

(xx) Raising the drilling mud weight above the *frac gradient* will lead to

(a) breakouts.

(b) drilling induced tensile fractures.

(c) washouts.

(xxi) True or False? If we idealize the earth's surface as a half-space, the vertical stress due to overburden is a principle stress.

(a) True

(b) False

(xxii) In the context of characterizing a fault, the *dip* angle is

(a) the angle of the fault strike with respect to north.

(b) the angle of the fault plane with respect to horizontal.

(c) the angle that defines the displacement vector of the fault slip motion measured from horizontal.

(xxiii) A central finite-difference approximation for a function discretized on a one-dimensional grid with uniform grid spacing of h has error

(a) $\mathcal{O}(h)$

(b) $\mathcal{O}(h^2)$

(c) $\mathcal{O}(h^3)$

(xxiv) According to Anderson fault classification, the principle stress magnitudes have the following ordering for a normal faulting regime.

(a) $S_v > S_{Hmax} > S_{hmin}$

(b) $S_{Hmax} > S_v > S_{hmin}$

(c) $S_v > S_{hmin} > S_{Hmax}$

(xxv) True or False? A good rule of thumb for estimating the overburden stress in the continental crust is that the stress increases by 0.44 psi/ft.

(a) True

(b) False

(xxvi) True or False? A typical value of Biot's coefficient for petroleum reservoir rocks would be $0.6 < \alpha < 1.0$.

(a) True

(b) False

(xxvii) If we are given the three principle stresses S_v, S_{Hmax}, and S_{hmin}, what else is needed to fully characterize the tectonic stress field.

(a) The direction of either S_{Hmax} or S_{hmin}

(b) The dip and strike angles of the nearest fault

(c) The type of faulting regime according to Anderson classification.

(xxviii) The Cauchy stress tensor is always symmetric due to what principle?

(a) Conservation of linear momentum

(b) Conservation of angular momentum

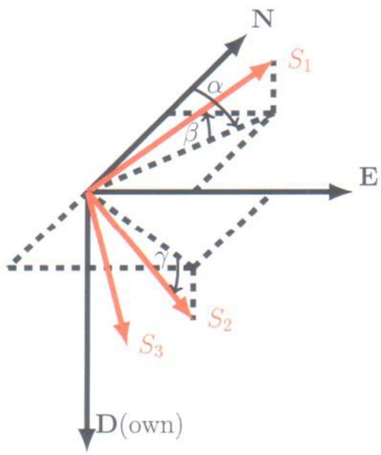
(c) Conservation of energy

(xxix) True or False? A lithostatic pore pressure is one in which the ratio of pore pressure to S_v is exactly 0.44.

(a) True

(b) False

(xxx) Consider the following figure:



If S_1 was initially in the direction of **N**, which rotation would reorient S_1 so that it is consistent with an Andersonian normal faulting regime with.

(a) $\gamma = 90°$

(b) $\beta = -90°$

(c) $\alpha = -90°$

Problem 2

(**5 points**) For the following matrix $\mathbf{A}$,

$$\mathbf{A} = \begin{bmatrix} -2 & 1 \\ 1 & -2 \end{bmatrix}$$

Compute the eigenvalues of $\mathbf{A}$ **by hand**.

$$A - \lambda I = \begin{bmatrix} -2 & 1 \\ 1 & -2 \end{bmatrix} - \lambda \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} -2-\lambda & 1 \\ 1 & -2-\lambda \end{bmatrix}$$

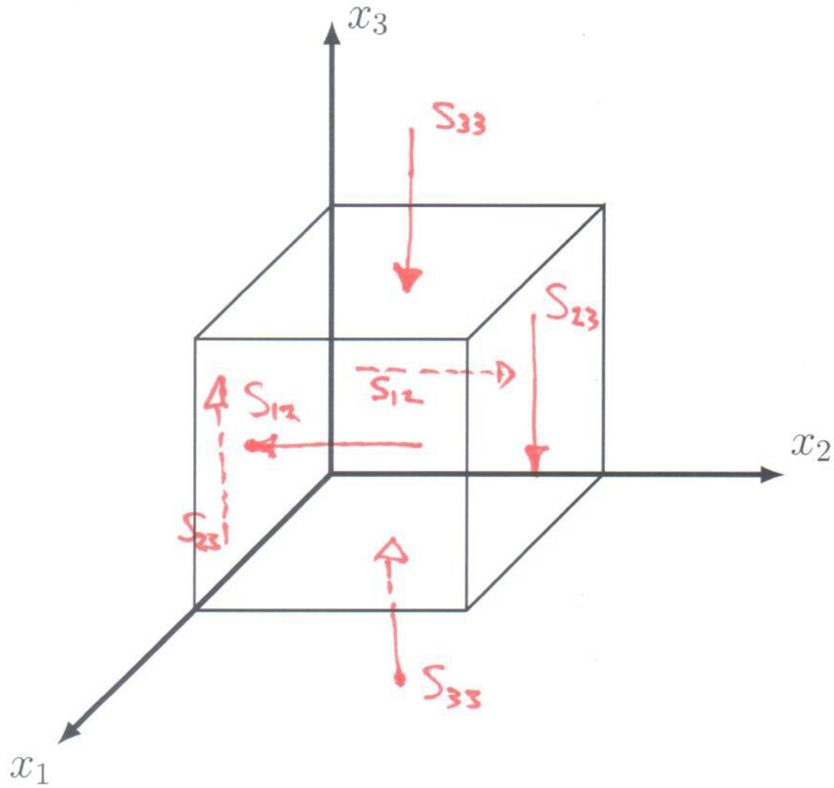
$$\det(A - \lambda I) = (-2-\lambda)(-2-\lambda) - 1 = \lambda^2 + 4\lambda + 3 = 0$$

$$(\lambda+3)(\lambda+1) = 0$$

$$\boxed{\lambda_{1,2} = \{-1, 3\}}$$

Problem 3

(5 points) Consider the following figure:



On the figure, correctly indicate (with hand-drawn arrows) the stress components S_{23}, S_{33}, and S_{12} on both sides of the cube where they act (use a compression-positive sign convention). You must get this exactly correct, no partial credit will be given on this answer.

Problem 4

(5 points) A producing well was initially hydraulically fractured during completion and principle stress measurements of $S_{Hmax} = 65$ MPa and $S_{hmin} = 62$ Mpa where made at the time in a Andersonian normal faulting regime. The reservoir has poroelastic properties $\nu = 1/4$ and $\alpha = 1$. After draw-down from an initial pore pressure of 60 MPa to 40 MPa over a number of years, the well is being considered for a re-fracturing treatment. Given what you know, would this likely be an effective stimulation? Provide analysis to support your answer.

The principle horizontal stresses are close enough that the isotropic approximation and

$$\Delta S_{Hor} \sim \frac{2}{3} \Delta P$$

are good estimates. Given that $\frac{2}{3}\Delta P \approx 13$ MPa. There is a good chance of stress reversal under these conditions. Stress reversal would allow new fractures to access new parts of the reservoir, so this would likely be a good candidate for refracturing.

Problem 5

(5 points) A crack opening displacement is measured as 1 mm a distance 1 m from a crack tip in an elastic media with properties $E = 50$ GPa and $\nu = 0.2$ under plain strain conditions. If this material has a fracture toughness value of $K_{Ic} = 15$ MPa would this crack be expected to propagate?

Here are a few relationships between the elastic constants if needed:

$$K = \frac{E}{3(1-2\nu)}, \qquad \lambda = \frac{E\nu}{(1+\nu)(1-2\nu)}, \qquad \mu = \frac{E}{2(1+\nu)}$$

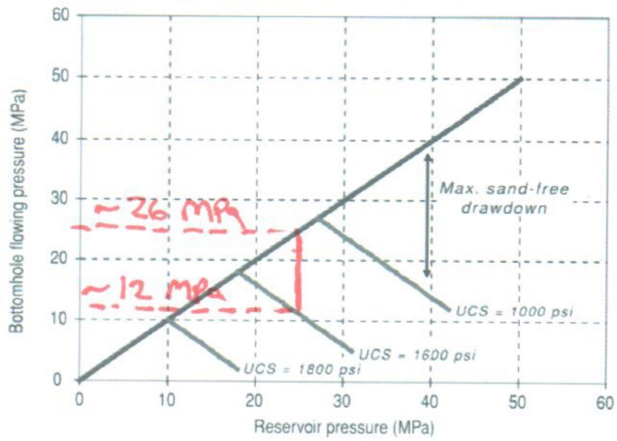
$$K_I = \frac{\mu}{4(1-\nu)}\sqrt{\frac{2\pi}{r}}\,[[u_I]] = \frac{E}{8(1-\nu)(1+\nu)}\sqrt{\frac{2\pi}{r}}\,[[u_I]]$$

$$= \frac{50 \times 10^9 \text{ Pa}}{8(1-0.2)(1+0.2)}\sqrt{\frac{2\pi}{1 \text{ m}}}\,(0.001 \text{ m}) \approx \underline{16 \text{ MPa}}$$

Since $K_I > K_{Ic}$ the crack <u>would</u> propagate.

Problem 6

(2 points each) Consider the figure created from a complete geomechancal model used to predict sand production under given reservoir conditions.



(i) Circle the best answer: For a pore pressure of 30 MPa and bottom hole pressure of 20 MPa, would a material with an unconfined compressive strength of 1000 psi produce sand? (Excuse the mixed units...)

(a) Yes

(b) No

(ii) Estimate the maximum drawdown pressure for a material with an unconfined compressive strength of 1600 psi at a reservoir pressure of 25 MPa.

$\boxed{\simeq 14 \text{ MPa}}$

Problem 7

(20 points)

A fault is found at 2 km depth with strike N10°E and dip 40°. Wellbore breakouts in a vertical well drilled through this portion appear at N20°E, and horizontal stresses are estimated at $S_{hmin} = 50$ MPa and $S_{Hmax} = 85$ MPa. The lithostatic vertical stress gradient is 23 MPa/km.

At what pore pressure would you expect the above described fault to slip? (Assume a friction coefficient $\mu = 0.6$). If it were to slip, what type of fault motion would you expect (be as specific as possible)?

From breakouts: S_{hmin} is in direction N20°E

$S_{Hmax} = 85$ MPa, $S_{hmin} = 50$ MPa, $S_v = 46$ MPa

$S_{Hmax} \downarrow S_1$, $S_{hmin} \downarrow S_2$, $S_v \downarrow S_3 \rightarrow \alpha = -70°$

$\beta = 0°$

$\gamma = 0°$

$$S = \begin{bmatrix} 85 & 0 & 0 \\ 0 & 50 & 0 \\ 0 & 0 & 46 \end{bmatrix} \quad \text{From Matlab } S_G = R_G^T \cdot S \cdot R_G = \begin{bmatrix} 54.09 & -11.29 & 0 \\ -11.29 & 80.95 & 0 \\ 0 & 0 & 46 \end{bmatrix}$$

strike = 10° dip = 40°

From Matlab

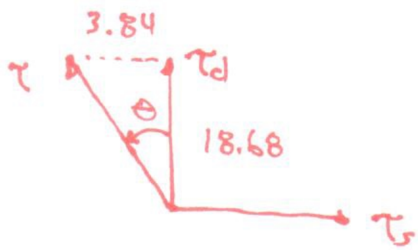
$S_n = (S_G \cdot \hat{n}) \cdot \hat{n} = 61.67$, $\tau_s = (S_G \cdot \hat{n}) \cdot \hat{n}_s = -3.847$

$\tau_d = (S_G \cdot \hat{n}) \cdot \hat{n}_d = 18.68$, $\tau = \sqrt{\tau_d^2 + \tau_s^2} = 19.076$

This page provided for additional calculations

For slip to occur

$$\frac{\tau}{(S_n - P_p)} = \mu \Rightarrow P_p = S_n - \frac{\tau}{\mu} \approx \boxed{30 \text{ MPa}}$$



$$\tan(\theta) = \frac{3.84}{18.68} \Rightarrow \theta \approx 12^\circ$$

Because θ is very small $\rightarrow$ $\boxed{\text{Normal fault}}$

Problem 8

Extended-reach *horizontal* wellbores are being drilled from an offshore platform in Gulf of Mexico. Wellbore stability issues are being encountered because of over-pressured shales. The problematic formation is found at 2 km depth below the seafloor and 3 km (true vertical) depth from the drilling rig. The minimum horizontal stress is 48 MPa, and the vertical stress is 58 MPa. All of the questions below refer to wells drilled parallel to S_{Hmax}.

(a) **(10 points)** Estimate vertical stress on your own and compare with the true value given above ($S_v = 58$ MPa). What could cause the difference?

(b) **(10 points)** Given laboratory measurements $\lambda_p = 0.75$, $C_0 = 30$ MPa, $\mu_i = 0.9$ and tensile strength $T = 3$ MPa, determine the wellbore pressure for initiation of breakouts and tensile fractures.

(c) **(6 points)** In case breakouts form, would you expect them on the sides or top-bottom of the wellbore?

(a) $S_v = S_{water} + S_{ROCK}$

$$= (10 \text{ MPa/km}) \cdot 1 \text{ km} + (23 \text{ MPa/km}) \cdot 2 \text{ km} = \boxed{56 \text{ MPa}}$$

Density variations in rock can cause the difference

(b) $\lambda_p = \dfrac{P_p}{S_v} \Rightarrow P_p = (58 \text{ MPa})(0.75) = 43.5 \text{ MPa}$

In horizontal well, Kirsh solutions are valid $S_v \Leftrightarrow S_{Hmax}$ in this case.

$$\sigma_{\theta\theta}^{max} = 3S_v - S_{hmin} - 2P_p - (P_m - P_p) \qquad \sigma_{rr} = P_m - P_p$$

Mohr-Coulomb model

$$\underbrace{\sigma_1}_{\sigma_{\theta\theta}^{max}} = C_0 + q \underbrace{\sigma_3}_{\sigma_{rr}} \Rightarrow \text{Solve for } P_m$$

$$P_m = \frac{3S_v - S_{hmin} - C_0 - P_p + P_p q}{1+q} \boxed{= 49 \text{ MPa breakouts}}$$

$$q = \left(\sqrt{\mu_i^2 + 1} + 1\right)^2$$

This page provided for additional calculations

$\sigma_{\theta\theta}^{min} = 3S_{hmin} - S_v - P_p - P_m = -T$

Solve for P_m

$P_m = 3S_{hmin} - S_v - P_p + T \simeq$ $\boxed{\text{46 MPa for tensile fractures}}$

(c) Breakouts occur at azimuth of S_{hmin}, which would be on the sides of wellbore in this case.