Geol 326-00
11 May 1999

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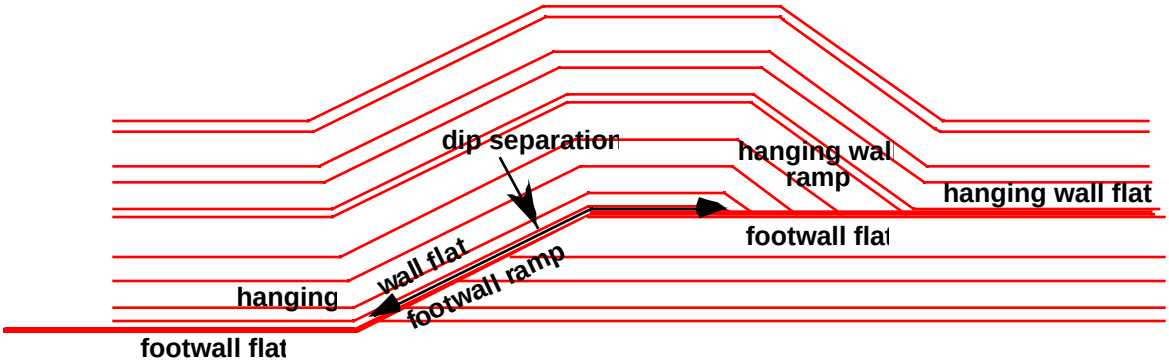
Geol 326-00 Final Exam

Class Average: 143/200
Std. Dev = 25

This exam is closed book and closed notes. Please be sure to show all of your work. There are two pages of potentially useful equations at the back of the exam. The point value of each question is shown. The total value of the exam is 200 points (out of 800 for the class).

1. The following questions apply to the "ramp & flat" model of folds in thrust belts.

   (a) Make a careful drawing of a cross section of a hanging wall (or fault-bend fold) anticline and its associated fault. Be sure to label the ramps and flats. Show the amount of dip separation. **[15 pts.]**



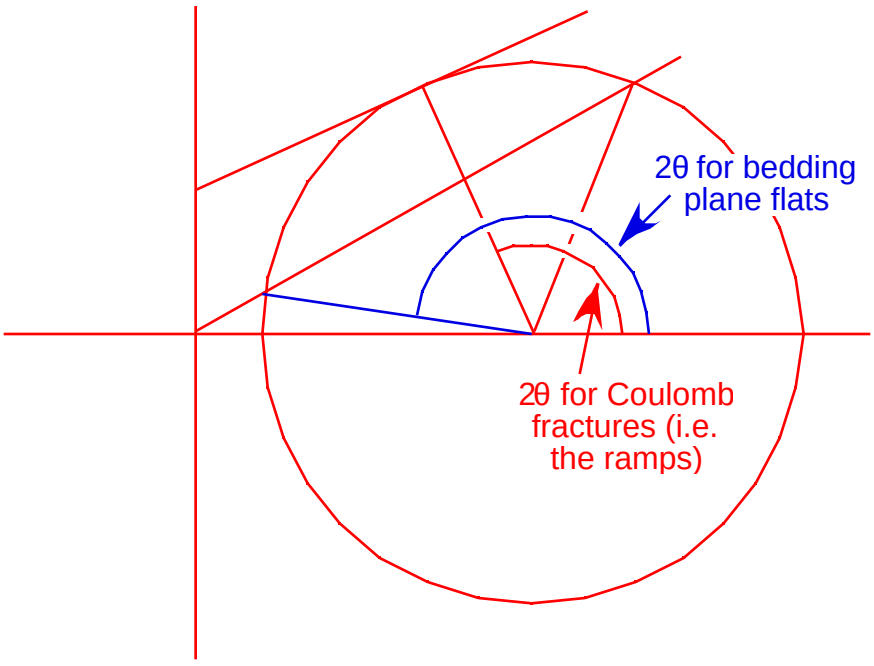
   (b) If the 2-D length of the bedding surfaces in the plane of the section does not change as the upper plate moves over the lower plate, what type of kinematic model will the folds conform to, and why? **[15 pts.]**

The fact that bedding doesn't change length means that the means that the bedding is a line of no finite elongation and the shear must be parallel to bedding (remember the card deck experiment where the cards don't change length as you shear parallel to them). This type of fold kinematic model is parallel folding which has class 1b dip isogons.

(c) Assuming that Anderson's Law holds and that the coefficient of internal friction is 0.73, what angle would you expect the fault ramps to form at and why? Discuss the ramp and flat geometry in terms of Anderson's Law. **[15 pts.]**

Anderson's Law says that faults are Coulomb Fractures and that, because there is no shear stress parallel to the surface of the Earth, one of the principal stresses must be perpendicular to the surface. For thrust faults, σ_3 will be perpendicular and σ_1 parallel. If we assume that the surface was flat before the thrust formed (which is consistent with Dahlstroms Rules about previously undeformed strata being involved in the thrusting), then the fault ramps ought to form at a dip angle of $45 - \varphi/2 = 45 - \tan^{-1}(0.73)/2 = 45 - 18 = 27°$

As we can see above, the ramp angles are well accounted for by Anderson's Law. But what about the flats? Anderson's law certainly does not predict flat lying faults! Part of the answer lies in the fact that the flats are essentially pre-existing nearly cohesionless surfaces and therefore are not Coulomb fractures at all.

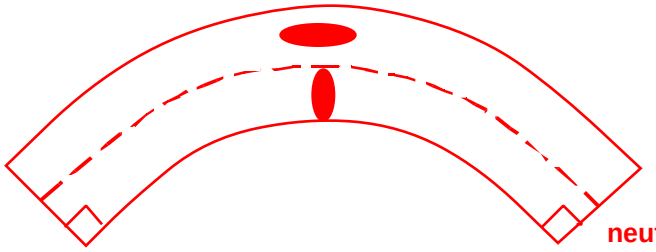


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2. (a) Compare and contrast buckling and Gaussian curvature. Can both apply to a single layer simultaneously? **[15 pts.]**

First and foremost, Gaussian curvature applies to a surface or sheet of infinite thickness whereas buckling applies to a layer of finite thickness. Thin bedding in geology may approximate a Gaussian surface. In Buckling, there is a neutral surface within the layer, with extension on the outer arc and shortening on the inner arc, with no shear parallel to the layer:



Either buckling or Gaussian curvature can be involved with the formation of cylindrical folds, including parallel, flexural slip folds, as long as the layer parallel shear does not occur within the buckled layer, itself.

(b) What would you look for in the rocks to determine which model was most appropriate in any given situation? **[10 pts.]**

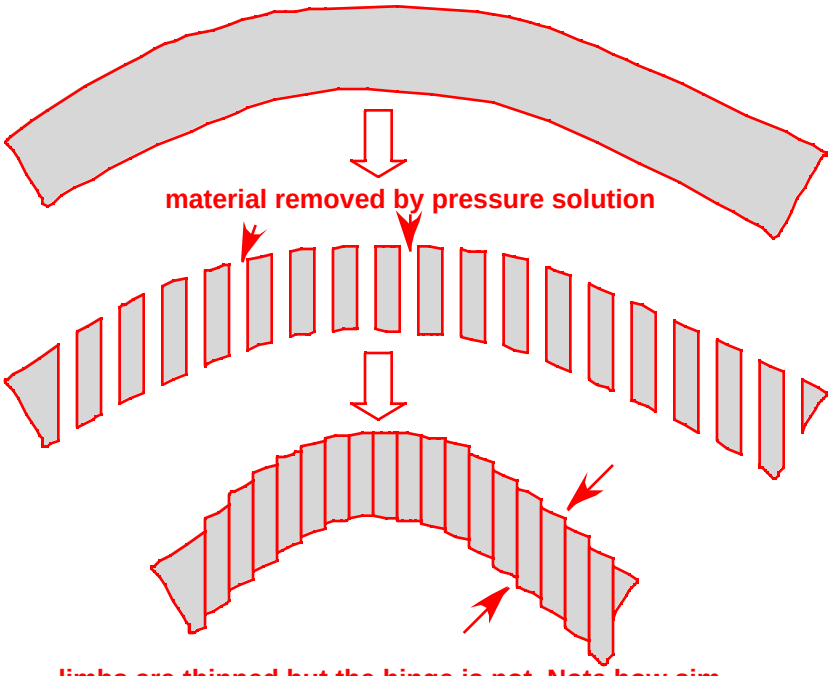
In the case of Gaussian curvature, you would look to see if there was a line in the surface which had zero curvature; if so then the surface was deformed with the Gaussian curvature before and after equal, and the fold is a cylindrical fold.

For buckling, you would look for evidence of a neutral surface and for features documenting a lack of shear parallel to the layer. Features indicative of layer parallel extension above the neutral surface include veins and normal faults; shortening below the neutral surface would be indicated by thrust faults and layer perpendicular stylolites.

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3. Describe how folds with class 2 dip isogons might be produced by pressure solution cleavage. How would these differ from the common explanation for these folds? **[15 pts.]**

Folds with class 2 dip isogons are similar folds in which the bedding thickness on the limbs is different from that on the hinge. Once the limbs have some initial dip by some folding mechanism, their dip can be steepened and their thickness measure perpendicular to bedding reduce by pressure solution as shown in the diagram, below:



limbs are thinned but the hinge is not. Note how simple volume removal causes steepening of the limbs without any actual rotation of material

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4. The following questions pertain to S-C mylonites:

(a) Make a careful sketch of S and C planes in a left lateral shear zone. Be sure to label the planes and show where you would expect the highest strains to be found. **[10 pts.]**



(b) Assuming that the two planes formed at the same time, what is the maximum angle that you would expect the S planes to make with respect to the C planes. Explain your answer in precise terms. **[10 pts.]**

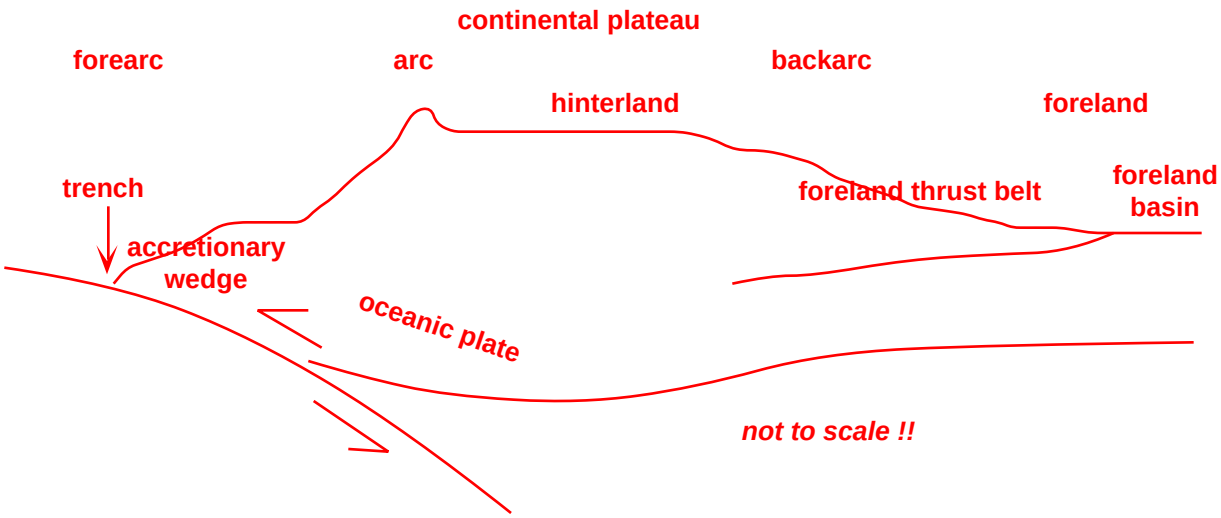
Here we assume that the S-planes are parallel to the longest principal axis of the finite strain ellipse. The infinitesimal axes of strain are oriented at 45° to the plane of maximum shear strain. Therefore the largest angle that the S and C planes should make with respect to each other is 45° (at least theoretically).

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5. The Central Andes are the type example of a mountain belt formed at a plate boundary where oceanic crust is being subducted beneath continental crust. The density of the crust is 2700 kgm^{-3} and the density of the underlying mantle is 3300 kgm^{-3}.

   (a) Make a sketch cross section, from the plate boundary to the foreland, showing (and labeling) the main tectonic elements of this mountain belt. **[15 pts.]**



   (b) The Altiplano of the Central Andes is a high plateau at an average elevation of 4 km above sea level. The thickness of the crust beneath this plateau has been measured to be 70 km thick. Assuming local Airy isostasy, calculate the thickness of the crust beneath the adjacent foreland of eastern Bolivia, where the elevation is just 300 m. Explain all assumptions that you have made in making this calculation. **[15 pts.]**

We have the following two equations from differential isostasy, which we solve for the change in crustal thickness:

$$\rho_c \Delta h_c + \rho_m \Delta h_m = 0 \quad \rightarrow \quad \Delta h_m = \frac{-\rho_c \Delta h_c}{\rho_m}$$

and

$$\Delta E = (4km - 0.3km) = 3.7km = \Delta h_c + \Delta h_m$$

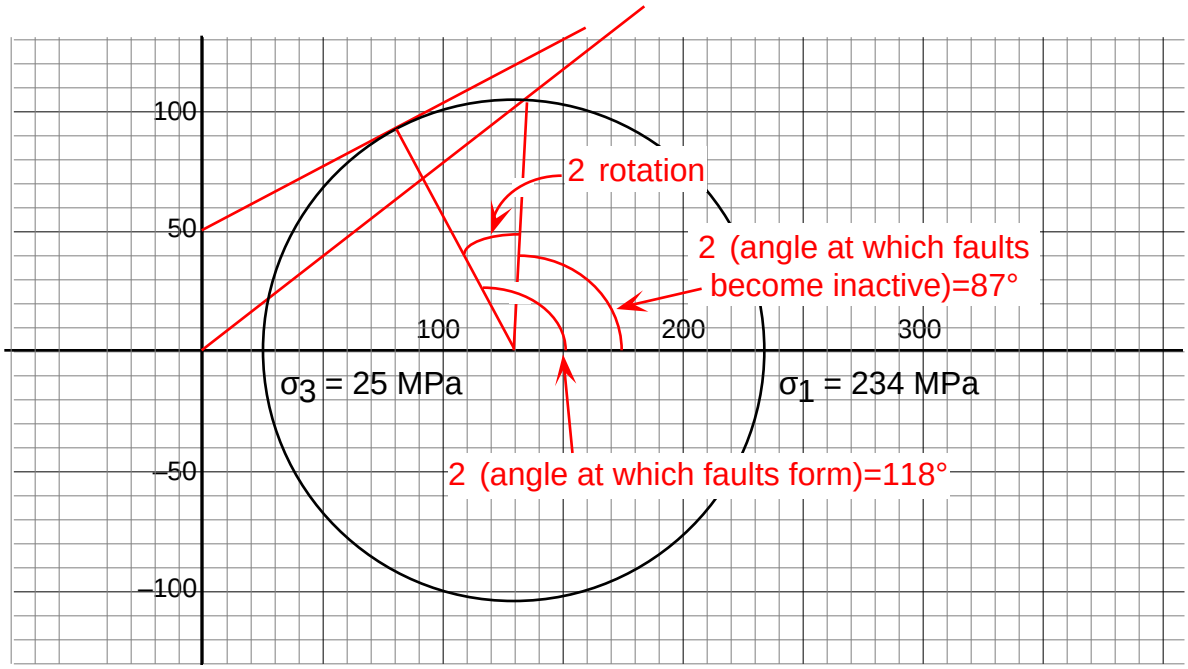
substituting and solving for Δh_c:

$$\Delta E = 3.7km = \Delta h_c - \frac{\rho_c \Delta h_c}{\rho_m} = \Delta h_c \left(1 - \frac{\rho_c}{\rho_m}\right) \quad \rightarrow \quad \Delta h_c = \frac{\Delta E}{\left(1 - \frac{\rho_c}{\rho_m}\right)} = \frac{3.7km}{\left(1 - \frac{2700}{3300}\right)} = 20.35km$$

Thickness of the crust beneath the foreland = 70 km - 20.35 km = 49.65 km. This number would be lower if the density contrast were less. Assumptions: local Airy isostasy, no flexure, no thermal uplift.

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6. In a region of intracontinental rifting, the extension occurs via domino faulting. In this area, the angle of internal friction is 28°, the coefficient of sliding friction is 0.8, the density is 2600 kgm^{-3} and the cohesion is 50 MPa. The state of stress is shown in the Mohr's Circle, below



(a) How deep in the crust would you expect to find the stresses represented on the Mohr's circle? **[10 pts.]**

If we assume that σ_1 is vertical and equal to the lithostatic stress then $\sigma_1 = \rho g z$, where z is the depth. Solving for z:

$$z = \sigma_1/(\rho g) = 234 \text{ MPa}/(2600 \text{ kgm}^{-3} * 9.8 \text{ ms}^{-1}) = 9184 \text{ m} = 9.184 \text{ km}$$

(b) Determine how much the domino faults will rotate before they become inactive and new set of faults begins to form. **[15 pts.]**

From the above Mohr's Circle, you can see that the faults form initially with a $2\theta = 118°$. Because these are normal faults and σ_1 is vertical θ is the same as the dip of the fault, so the faults form initially with a dip of 59°. As they rotate to lower dip angles, θ also decreases and when $\theta < 87°/2$, or a dip of 43.5° they will become inactive. So in this example, the faults rotate by just 15.5° before they stop moving.

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7. Define **any four** of the following six terms **[10 pts. each]**:

(a) Transposition

Transposition occurs when an initial compositional layering, such as bedding, is modified and changed into a new and different compositional layering by structural and metamorphic processes. It can be very misleading because it is commonly mistaken for the initial layering

(b) Microlithons

Microlithons, sometimes called QF (for quartz and feldspar) domains, are the remaining slivers of rock which occur between the cleavage (or M- for mica) domains.

(c) Piercing points

A linear feature intersects a future fault plane in a point. When the fault slips, the point of intersection in the hanging wall block and that in the footwall block – called "piercing points" – are offset. The only reliable way to determine the slip vector along a fault is to connect these piercing points.

(d) Buried focus

The buried focus is an artifact of seismic reflection data where a synclinal feature in the subsurface acts rather like a concave mirror. Buried focuses can produce a bow-tie geometry in unmigrated reflectors.

(e) Cataclasite

This an unfoliated, cohesive fault rock produced predominantly by fracturing, milling and grinding the rock into smaller fragments

(f) Fault line scarp

This is a topographic scarp that marks where an emergent fault intersects the Earth's surface, but the scarp itself is not coplanar with the fault plane. These are particularly common in emergent reverse faults where the scarp dips in the opposite direction from the fault plane.

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Potentially Useful Equations

$$\sigma_{\Delta T} = \frac{\alpha E \Delta T}{1-\upsilon}$$

$$\sigma_{ij} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix}$$

$$V_i = \frac{k_{ij}}{\eta}\left(\frac{dP_P}{dx_j}\right)$$

$$\sigma_n^* = \left(\frac{\sigma_1^* + \sigma_3^*}{2}\right) + \left(\frac{\sigma_1^* - \sigma_3^*}{2}\right)\cos 2\theta$$

$$\sigma_s = \left(\frac{\sigma_1^* - \sigma_3^*}{2}\right)\sin 2\theta$$

$$\lambda' = \left(\frac{\lambda_3' + \lambda_1'}{2}\right) - \left(\frac{\lambda_3' - \lambda_1'}{2}\right)\cos 2\theta'$$

$$\gamma' = \left(\frac{\lambda_3' - \lambda_1'}{2}\right)\sin 2\theta'$$

$$\tan\theta' = \tan\theta\frac{\sqrt{\lambda_3}}{\sqrt{\lambda_1}} = \tan\theta\frac{S_3}{S_1}$$

$$\sigma_s = S_o + \sigma_n^*\mu$$

$$\dot{\varepsilon} = C_o\left(\sigma_1 - \sigma_3\right)^n \exp\left(\frac{-Q}{RT}\right)$$

$$\dot{\varepsilon} = C_o(T)\frac{D\left(\sigma_1 - \sigma_3\right)}{d^n}$$

$$U = -\frac{C_1}{r} + \frac{C_2}{r^{12}}$$

$$P_{lith} = \int_0^z \rho g dz$$

$$\phi = \frac{V_f}{V_f + V_s}$$

$$\phi = \phi_o \exp(-az)$$

$$\Delta_v = \frac{V_{final} - V_{initial}}{V_{initial}}$$

$$e = \frac{l_f - l_i}{l_i}$$

$$e = \frac{\sin(\phi + \theta)}{\sin\phi} - 1$$

$$S = \frac{l_f}{l_i} = \sqrt{\lambda}$$

$$\lambda = S^2$$

$$\lambda' = \frac{1}{\lambda}$$

$$\sin 2\theta = 2\sin\theta\cos\theta$$

$$\cos^2\theta = \left(\frac{1 + \cos 2\theta}{2}\right)$$

$$\sin^2\theta = \left(\frac{1 - \cos 2\theta}{2}\right)$$

$$U_i = U_{oi} + E_{ij}dx_j$$

$$\begin{bmatrix} U_1 \\ U_2 \\ U_3 \end{bmatrix} = \begin{bmatrix} U_{o1} \\ U_{o2} \\ U_{o3} \end{bmatrix} + \begin{bmatrix} E_{11} & E_{12} & E_{13} \\ E_{21} & E_{22} & E_{23} \\ E_{31} & E_{32} & E_{33} \end{bmatrix}\begin{bmatrix} dx_1 \\ dx_2 \\ dx_3 \end{bmatrix}$$

$$\sigma_m^* = \frac{\left(\sigma_1 + \sigma_2 + \sigma_3 - 3P_f\right)}{3}$$

$$\sigma_1^* = C_o + K\sigma_3^*$$

$$K = \frac{1 + \sin\phi}{1 - \sin\phi} \quad ; \quad C_o = 2S_o\sqrt{K}$$

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$$\sigma_\tau = 0.85\sigma_n^*$$

$$\sigma_\tau = 50\ \text{MPa} + 0.6\sigma_n^*$$

$$(\alpha + \beta) = \frac{(1-\lambda_f)\mu_f + \beta}{(1-\lambda)k + 1}$$

R = 8.3144 x 10^{-3} kJ/mol °K
= 1.9872 x 10^{-3} kcal/mol °K

°K = °C + 273.16°

1 MPa = 10^6 kg/m s^2 = 10 bars

g = 9.8 m/s^2 = 980 cm/s^2

$\cos\alpha = \cos(trend)\cos(plunge)$
$\cos\beta = \sin(trend)\cos(plunge)$
$\cos\gamma = \sin(plunge)$

$\cos\alpha = \sin(strike)\sin(dip)$
$\cos\beta = -\cos(strike)\sin(dip)$[1]
$\cos\gamma = \cos(dip)$

$$\tan 2\theta' = \frac{2}{\gamma}$$

$$p_i = \sigma_{ij} l_j$$

$$L_d = 2\pi T_3 \sqrt{\frac{E}{6E_o}}$$

$$L_d = 2\pi T_3 \sqrt{\frac{\eta(S-1)}{6\eta_o(2S^2)}}$$

$$\Sigma\,\Delta M = 0 = \Delta M_w + \Delta M_s + \Delta M_c + \Delta M_m + \Delta M_a$$

[1]right hand rule for planes

$$0 = \Delta(\rho_w h_w) + \Delta(\rho_s h_s) + \Delta(\rho_c h_c) + \Delta(\rho_m h_m) + \Delta(\rho_a h_a)$$

$$\Delta E = \Delta h_w + \Delta h_s + \Delta h_c + \Delta h_m + \Delta h_a$$

$$\phi = \tan^{-1}\left[\frac{-\sin(\gamma-\theta)\left[\sin(2\gamma-\theta) - \sin\right.}{\cos(\gamma-\theta)\left[\sin(2\gamma-\theta) - \sin\theta\right] -}\right.$$

$$\phi = \theta = \tan^{-1}\left[\frac{\sin(2\gamma)}{2\cos^2(\gamma) - 1}\right]$$

$$p_1 = \sigma_{11} l_1 + \sigma_{12} l_2 + \sigma_{13} l_3$$
$$p_2 = \sigma_{21} l_1 + \sigma_{22} l_2 + \sigma_{23} l_3$$
$$p_3 = \sigma_{31} l_1 + \sigma_{32} l_2 + \sigma_{33} l_3$$

$$\beta = \theta - \varphi + (180 - 2\gamma)$$

$$C \equiv \frac{1}{r}$$

$$C_G = C_{max}\ C_{min}$$

$$\gamma = \tan\psi = 2\tan\left(\frac{\delta}{2}\right)$$

$$\gamma = \tan\psi \quad 0.0175(\delta)$$

$$\bar{s} = 2\bar{h}\tan\left(\frac{\delta}{2}\right)$$

$$\bar{s} \quad 0.0175\bar{h}(\delta)$$