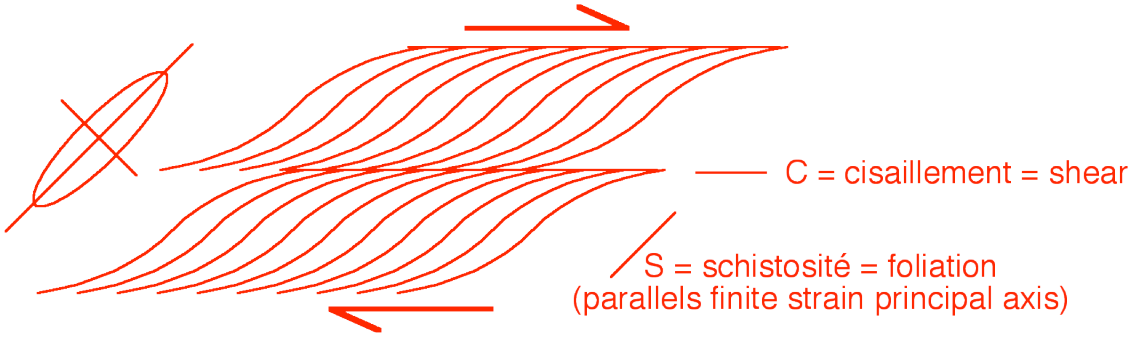
EAS 326-03 FINAL EXAM

This exam is closed book and closed notes. It is worth 150 points; the value of each question is shown at the end of each question. At the end of the exam, you will find two pages of potentially useful equations.

1. a. What are the similarities and differences among mylonites, breccia, and gouge? In your answer, be sure to explain the processes by which each form and where in the crust you would expect to find each one. **[15 pts.]**

Mylonites, gouge and breccia all form in fault zones. Gouge and breccia are usually unfoliated (although gouge may have a clayey foliation) and are the result of brittle grinding and milling of the rock particles in the fault zone. Gouge is generally non-cohesive and forms in the up few kilometers of the crust. Breccia can be more cohesive and may form somewhat deeper in the upper crust. Mylonites are always foliated and have had their grain size reduced by crystal plastic mechanisms, brittle grinding, or more likely a combination of the two. For example, it is common in some mylonites to see ductile deformation of quartz and brittle deformation of feldspars. Mylonites generally form a depths below 8-10 km (depending on the heat flow).

b. Define "S-C fabrics" and state in which of the above rock types you would expect to find S-C fabrics. **[10 pts.]**



S-C fabrics are coevally forming foliation (S) and shear (C) planes that are common in mylonites. They are excellent sense of shear indicators. Kinematically analogous features are also found in brittle shear zones.

c. Suppose that, midway between two C planes, the S planes make an angle of 34° with respect to the C planes. What would the angular shear and shear strain be at that point (i.e., midway between the two C planes)? **[15 pts.]**

From class, we have the relationship (initially from Ramsay & Graham) that:

$$\tan 2\psi = \frac{2}{\gamma} \quad \text{rearranging:} \quad \gamma = \frac{2}{\tan 2\psi} = \frac{2}{\tan 2 * 34} = 0.808$$

The angular shear is:

$$\psi = \tan^{-1}\gamma = \tan^{-1} 0.808 = 38.9°$$

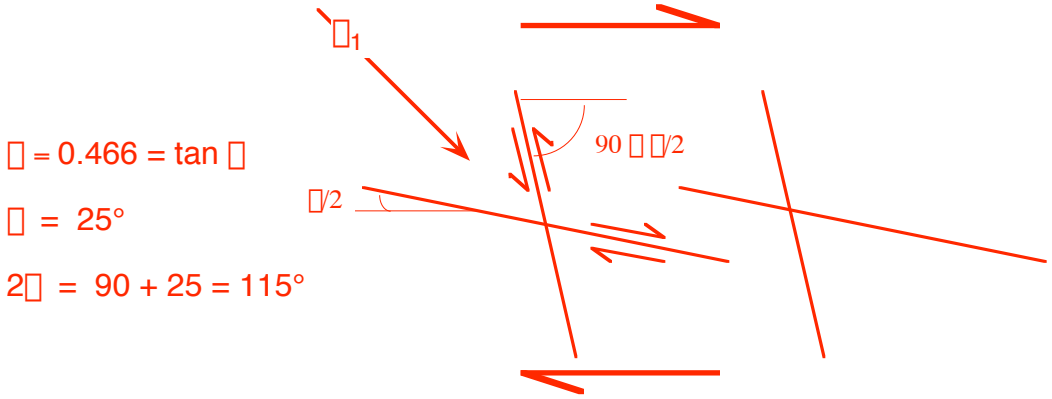
d. In a different rock, you found some S planes that were oriented at 67° to the some C planes. What would you conclude about the relationship between these two foliations in this rock and why? **[10 pts.]**

You would conclude that the two foliations are most likely unrelated to each other. Probably the S planes formed first. We know that the axes of the infinitesimal strain ellipse are oriented at 45° to the boundaries of the shear zone and that, with increasing shearing and strain, the angles between shear zone boundary and the finite strain ellipse are less (remember our virtual card deck experiment). Thus there is no way that, if the S and C planes formed at the same time that the S planes could be at a higher angle than 45°.

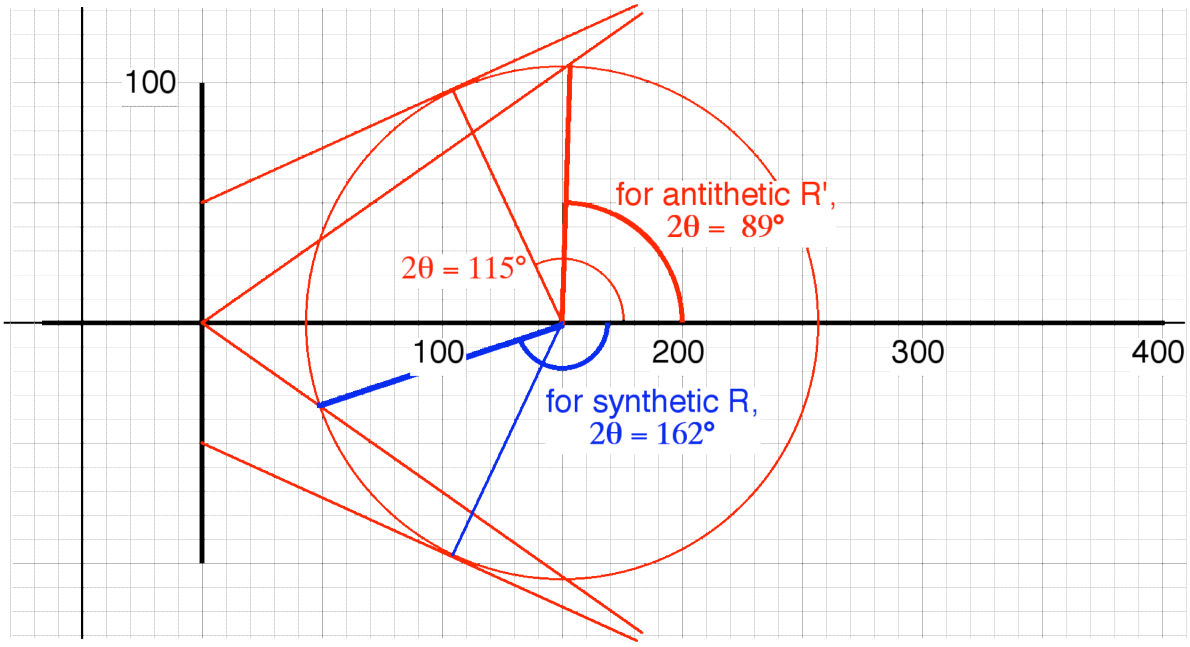
2. Riedel shears are produced in a right-lateral brittle shear zone. The pertinent properties of the rock and the stresses on it are shown in the table at the right. For all of the following questions, assume that the orientations and magnitudes of the stresses are constant (even if that assumption may not be very realistic…).

Coefficient	Symbol	Amount
internal friction	μ	0.466
sliding friction	μ_s	0.700
cohesion	S_o	50 MPa
max. principal stress	σ_1	258 MPa
confining pressure	P_c	42 MPa

a. The shear zone is shown below. Draw the orientations of the principal stresses and both sets of Riedel shears. Be sure to show (and label) their correct angular relations with respect to the shear zone boundaries. **[10 pts.]**



b. Plot the Mohr's Circle for stress and the failure envelopes for Coulomb fracture and for slip along pre-existing faults. Be sure to label your diagram! **[15 pts.]**

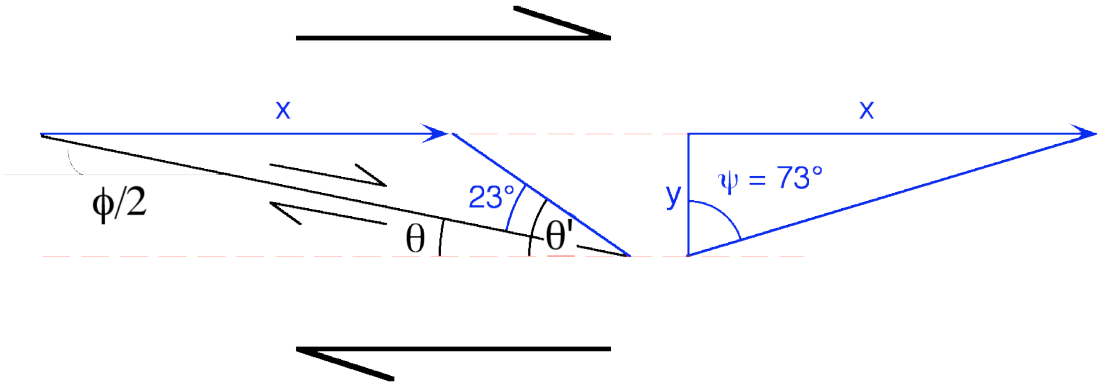


c. How much, and in what direction, will the synthetic (R) and antithetic (R') Riedel shears rotate before they become inactive? **[10 pts.]**

Both the R and R' shears will rotate clockwise because the shear zone is right lateral. The R' shears will rotate (115 - 89)/2 = 13° before they become inactive (note that the R' shears plot above the X-axis because the way we derived Mohr's Circle, left lateral shear is positive). The R shears will rotate (162 - 115)/2 = 23.5° before they become inactive.

d. How much shear strain or angular shear will the shear zone have to experience before the synthetic Riedels become inactive? You can solve this problem graphically or trigonometrically. **[10 pts.]**

The figure below shows the graphical construction:



You can also solve the problem trigonometrically:

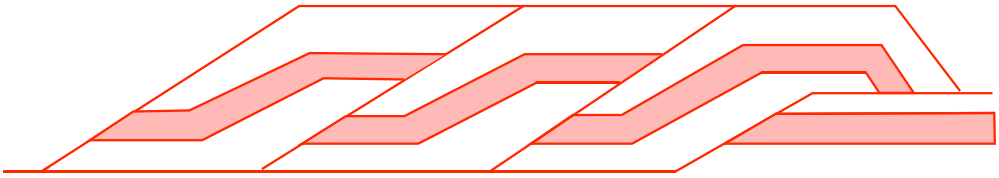
$$\tan\psi = \frac{y}{\frac{y}{\tan\phi} - y\tan\phi}$$

rearranging to solve for y:

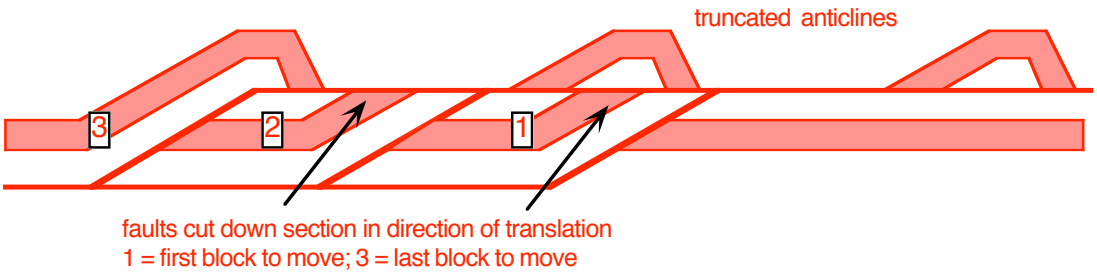
$$\tan\psi = \frac{1}{\tan\phi} - \frac{1}{\tan\theta} = \frac{1}{\tan(12.5)} - \frac{1}{\tan(12.5+23.5)} = 3.1343 \quad \Rightarrow \quad \psi = 72.3°$$

3. A characteristic feature of thrust belts is the duplex. How would you distinguish between and "in sequence" duplex that follows Dahlstrom's rules and an out of sequence duplex that does not? Make a careful sketch of each type to illustrate your answer. **[15 pts.]**

A normal in-sequence duplex is shown below. Notice that there is no truncation off beds on the roof thrust. All faults obey Dahlstrom's rules and cut upsection in the direction of translation.

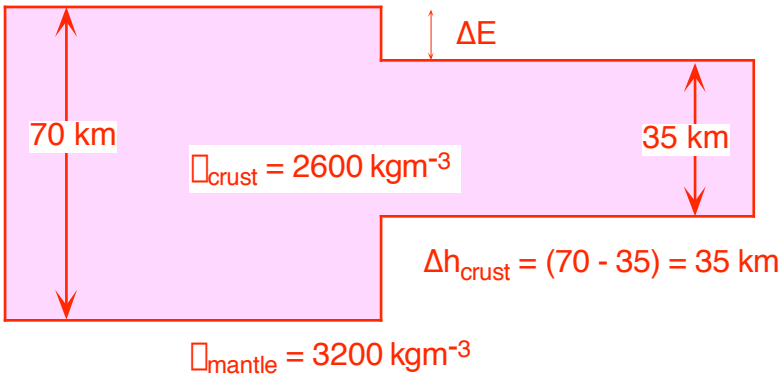


An out of sequence duplex is shown below. It is characterized by truncation on the roof thrust and "beheaded" anticlines, resulting in the fault locally cutting down-section in the direction of translation.



4. a. Thrusting in a mountain range has produced 50% shortening (e = −0.5) during a plane strain, constant volume deformation. Assume that the crust prior to deformation was a sea level and was 35 km thick, and that the crustal density is 2600 kg m^{-3} and that of the mantle 3200 kg m^{-3}. How high will the mountain belt be and thick will its root be (assuming no erosion)? What is the basic assumption of your calculation? **[15 pts.]**

50% shortening in plane strain, constant volume means that the crustal thickness will double from 35 to 70 km as shown below. Thus, we know that Δh_{crust} = (70–35) = 35 km.



From differential isostasy, we know that:

$$\Delta E = \Delta h_{crust} + \Delta h_{mantle} \qquad \text{and} \qquad \rho_{crust}\Delta h_{crust} + \rho_{mantle}\Delta h_{mantle} = 0$$

Thus, we have two equations with two unknowns, and we can solve them for ΔE:

$$\Delta E = \frac{\Delta h_{crust}\left(\rho_{mantle} - \rho_{crust}\right)}{\rho_{mantle}} = 6.56km$$

and the root will be 35 km - 6.56 km = 28.44 km. Note that the extreme elevation obtained in this problem results primarily because I gave you an unrealistically low average density for the crust!

The basic assumption here is Airy Isostasy and that the crust has no lateral strength (i.e., flexural rigidity).

b. Assume that the crust beneath this mountain range has a geothermal gradient of 30°C/km and has a granitic composition with the following parameters: $C_o = 10^{1.6}$ $GPa^{-n}s^{-1}$; n = 3.4; and the activation energy, Q = 139 kJ mol^{-1}. Furthermore you should assume a geologically reasonable strain rate. Calculate the maximum differential stress that crust can support at 20 km depth. Does this deformation conform to Anderson's Law? **[15 pts.]**

The solution to this problem calls for application of power law creep:

$$\dot{\varepsilon} = C_o\left(\sigma_1 - \sigma_3\right)^n \exp\left[\frac{-Q}{RT}\right] \quad \text{or} \quad \left(\sigma_1 - \sigma_3\right) = \left[\frac{\dot{\varepsilon}}{C_o \exp\left[\frac{-Q}{RT}\right]}\right]^{\frac{1}{n}}$$

$$= \left[\frac{10^{-14}\,s^{-1}}{10^{1.6}\,GPa^{-n}s^{-1}\exp\left[\frac{-139kJmol^{-1}}{\left(8.3144\times10^{-3}kJmol^{-1}K^{-1}\right)\left(\left(20km\times30°Ckm^{-1}\right)+273\right)K}\right]}\right]^{\frac{1}{3.4}} = 7.209\,MPa$$

This deformation, of course, has nothing to do with Anderson's Law because it is well below the free surface and because the deformation is not Coulomb fracture.

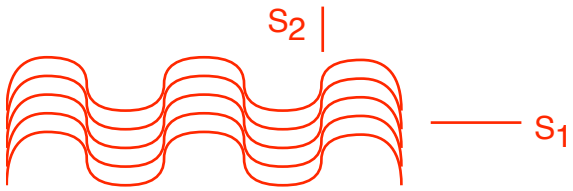
5. Define the following terms, mentioning, where appropriate, the processes responsible for, or the kinematic significance of, the feature (use sketches freely!):

   a. Transposition **[10 pts.]**—

   Transposition is the conversion of an original planar fabric (e.g., bedding) into a second planar compositional layering which has no stratigraphic relationship to the first. The processes involved include isoclinal folding and shearing out of the fold limbs. One can recognize transposition often by identifying remnant fold hinges, etc.

   b. crenulation cleavage **[10 pts.]**—

   Crenulation cleavage is a secondary cleavage superimposed on an earlier cleavage. In the drawing below, the crenulation cleavage is S_2:

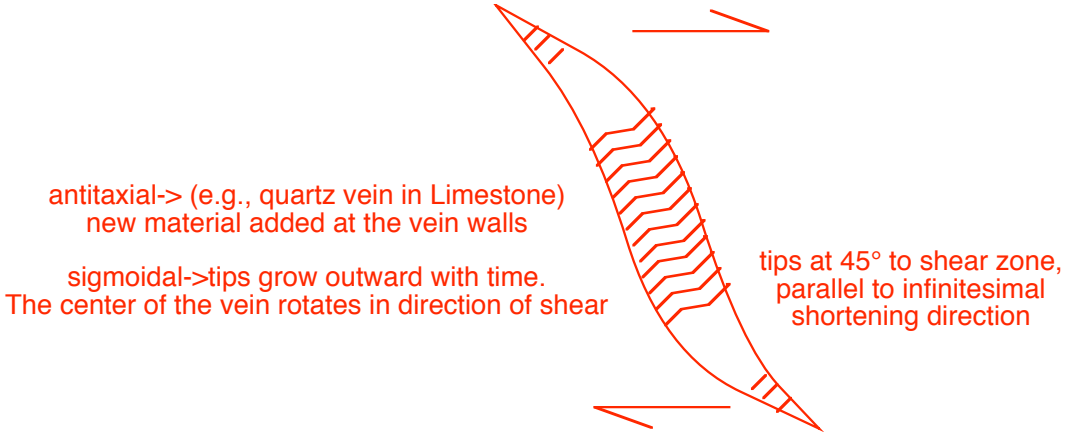


   The processes involved are primarily microfolding and pressure solution.

   c. parallel folding **[10 pts.]**—

   Parallel folds have Class 1b dip isogons. The thickness of the layer measured perpendicular to bedding is constant. The shear is parallel to the layers (a process known as flexural slip/flow) and therefore, the bedding surfaces are lines of no finite elongation.

   d. antitaxial, sigmoidal veins **[10 pts.]**—



6. Compare and contrast mode II (sliding) and mode III (tearing) cracks with edge and screw dislocations in crystals. **[20 pts.]**

Mode II cracks are similar to edge dislocations because the slip vector is perpendicular to the tip line of the crack, just as in an edge dislocation the Burgers vector is perpendicular to the tangent vector. Likewise, in a mode III crack the slip vector is parallel to the tip line just as in the case of a screw dislocation the Burgers vector is parallel to the tangent vector.

However, cracks are a permanent rupture across the material, whereas the movement of a dislocation across a crystal leaves a perfect crystal in its wake (i.e., there is no plane across which bonds are permanently broken).

Potentially Useful Equations

Note that not all of these equations are needed for the exam and that some of them have not, or will not, be covered in class at all.

$$\varepsilon_{\Delta T} = \frac{\alpha E \Delta T}{1-\nu}$$

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

$$V_i = \frac{k_{ij}}{\phi}\left[\frac{dP_P}{dx_j}\right]$$

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

$$\tau_s = \left[\frac{\sigma_1^* - \sigma_3^*}{2}\right]\sin 2\theta$$

$$\sigma_{n'} = \left[\frac{\sigma_3 + \sigma_1}{2}\right] - \left[\frac{\sigma_3 - \sigma_1}{2}\right]\cos 2\theta_c$$

$$\tau_{n'} = \left[\frac{\sigma_3 - \sigma_1}{2}\right]\sin 2\theta_c$$

$$\tan\theta_c = \tan\theta\frac{\sqrt{\sigma_3}}{\sqrt{\sigma_1}} = \tan\theta\frac{S_3}{S_1}$$

$$\tau_s = S_o + \mu_n^*\sigma_n$$

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

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

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

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

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

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

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

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

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

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

$$\lambda = S^2$$

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

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

$$\cos^2\theta = \left[\frac{1 + \cos 2\theta}{2}\right]$$

$$\sin^2\theta = \left[\frac{1 - \cos 2\theta}{2}\right]$$

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

$$\begin{bmatrix} U_1 \\ U_2 \\ U_3 \end{bmatrix} = \begin{bmatrix} U_{o_1} \\ U_{o_2} \\ U_{o_3} \end{bmatrix} + \begin{bmatrix} E_{11} & E_{12} & E_{13} \\ E_{21} & E_{22} & E_{23} \\ E_{31} & E_{32} & E_{33} \end{bmatrix}\begin{bmatrix} dx_1 \\ dx_2 \\ dx_3 \end{bmatrix}$$

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

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

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

$$\tau_f = 0.85\sigma_n^*$$

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

$$(\sigma + \sigma) = \frac{(1 - \sigma_f)\sigma_f + \sigma}{(1 - \sigma)k + 1}$$

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

°K = °C + 273.16°

1 MPa = 106 kg/m s^2 = 10 bars

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

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

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

$$\tan 2\theta = \frac{2}{\sigma}$$

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

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

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

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

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

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

$$\sigma = \sigma\sigma + (180° - 2\sigma)$$

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

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

$$\sigma = \tan\sigma = 2\tan\left[\frac{\sigma}{2}\right]$$

$$\sigma = \tan\sigma - 0.0175(\sigma)$$

$$\bar{s} = 2\bar{h}\tan\left[\frac{\sigma}{2}\right]$$

$$\bar{s} - 0.0175\bar{h}(\sigma)$$

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

$$0 = -(\sigma_w h_w) + (\sigma_s h_s) + (\sigma_c h_c) + (\sigma_m h_m) + (\sigma_a h_a)$$

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