FAULT SLIP

Lab 13

The purpose of this lab is to develop your ability to evaluate the slip along faults. The lab has three parts. The first requires you to evaluate the slip at a point along a fault based on a single offset marker that is nearly planar. The second requires you to evaluate the slip at a point along a fault based on a pair of offset markers that can be considered to intersect in a line. The third part involves modeling the displacement accompanying the 1906 earthquake along the San Andreas fault in using a simple model based on two screw dislocations.

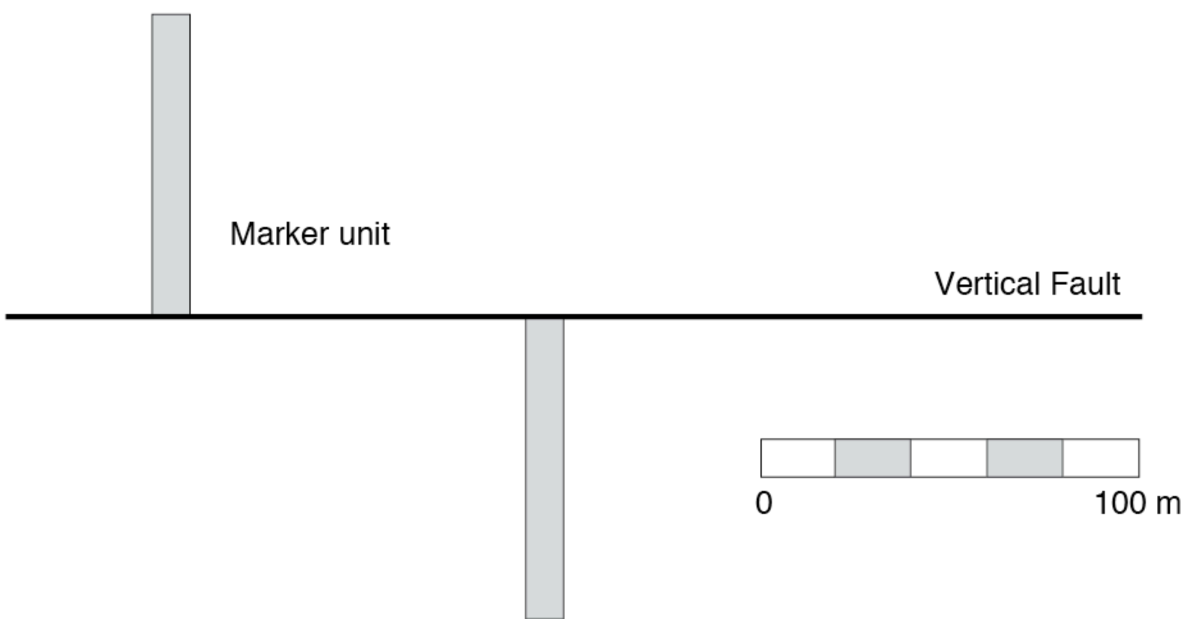
Problem 1 **(32 pts total)**

The map for problem 1, a faulted dike with a left-lateral separation of 100m. The mapped surface has been eroded perfectly flat. Consider the fault to strike east (this is for evaluating the rake of the slip). Consider the four cases below:

Case 1 The marker unit is vertical
Case 2 The marker unit dips 20° to the east and the fault is a pure dip-slip fault.
Case 3 The marker unit dips 20° to the west and the fault is a pure dip-slip fault.
Case 4 The marker unit dips 45° to the west and the vertical component of slip is 200 m, with the north side up.

You seek to find the slip for each case.

Problem 1



Questions

For each of the four cases, evaluate the slip.

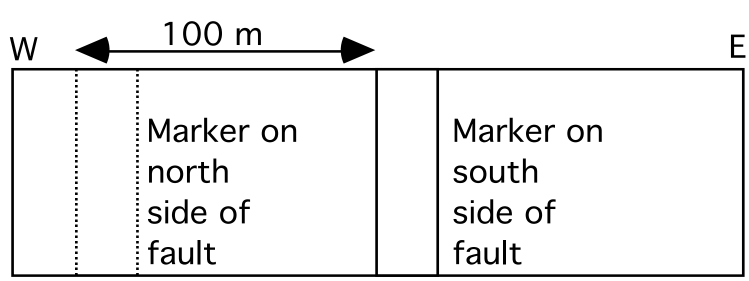
A What is the sense of slip? Dip-slip (north side up)? Dip-slip (south side up)? Left-lateral strike-slip? Right-lateral strike-slip? Oblique-slip? <u>If the sense of slip can not be determined uniquely, state the possible options.</u> <u>Be as specific as you can.</u>

B What are the horizontal, vertical and net components of slip (in meters)? If you can only give a minimum or a maximum figure, give that. If the amount of slip cannot be determined, state that.

C What would you expect for the trend and plunge of the slip vector? If the orientation of the slip vector cannot be determined, state that.

Case	Question A	Question B	Question C
1	Strike slip? Dip slip? (which side is up?) **2pts**	Horizontal_____1 Vertical_______1 Net__________1	Slip vector trend:________________ 1 Slip vector plunge:_______________ 1 Slickenside rake:_________________ 1
2	Strike slip? Dip slip? (which side is up?) **2pts**	Horizontal_____1 Vertical_______1 Net__________1	Slip vector trend:________________ 1 Slip vector plunge:_______________ 1 Slickenside rake:_________________ 1
3	Strike slip? Dip slip? (which side is up?) **2pts**	Horizontal_____1 Vertical_______1 Net__________1	Slip vector trend:________________ 1 Slip vector plunge:_______________ 1 Slickenside rake:_________________ 1
4	Strike slip? Dip slip? (which side is up?) **2pts**	Horizontal_____1 Vertical______1 Net__________1	Slip vector trend:________________ 1 Slip vector plunge:_______________ 1 Slickenside rake:_________________ 1

It might help to draw a cross section along the plane of the fault for each case. For example, for case 1 the cross section would look like so:



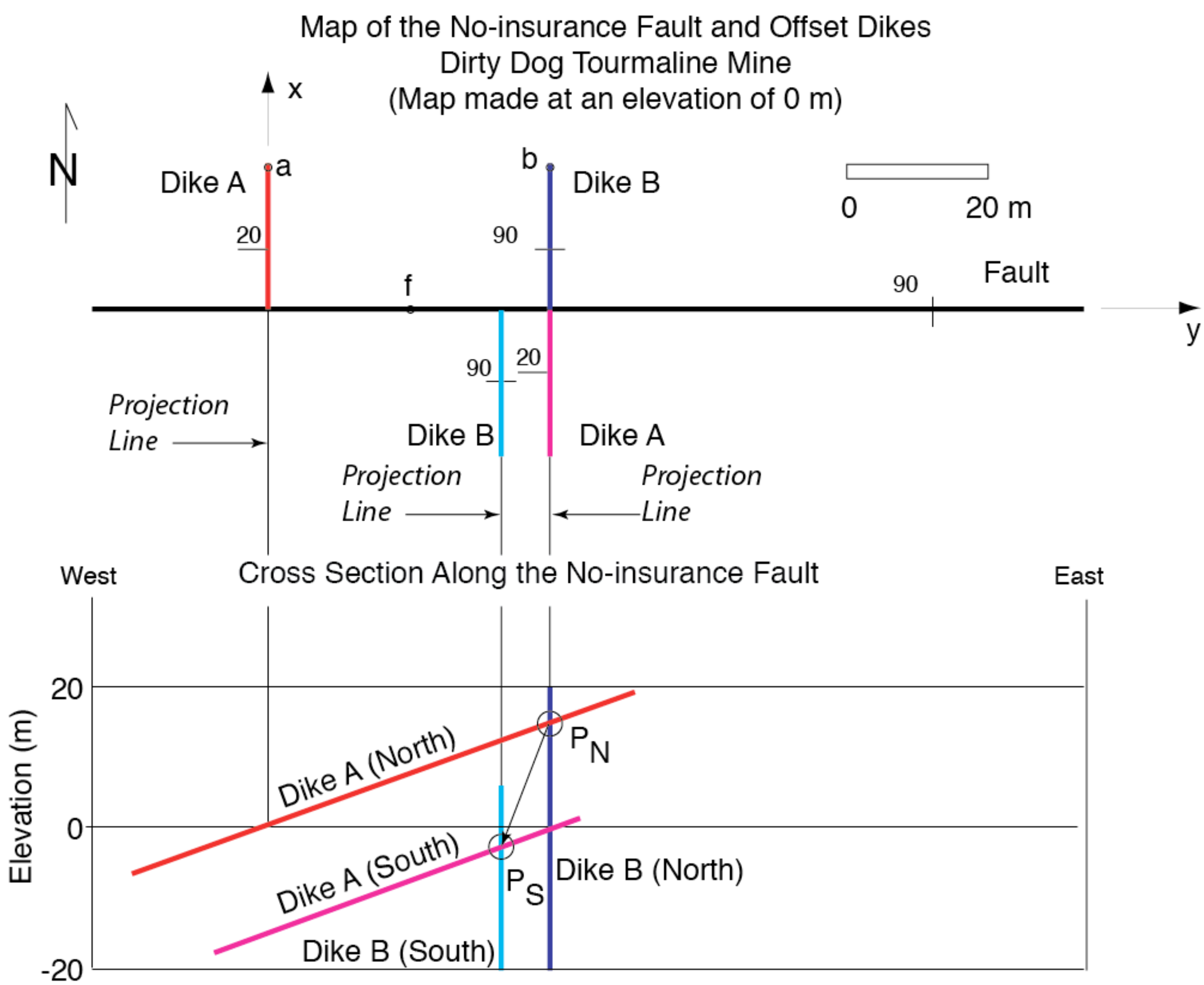
Problem 2 (32 pts total)

Review the example below before attempting problem 2.

In the example map and cross section below, two intersecting dikes of equal age are offset. They can be used together to find the slip across the fault. The dikes on each side of the fault can be considered to intersect in a line. The line on the north side of the fault intersects the fault to give one piercing point (P_N), and the line on the south side of the fault intersects the fault to give another piercing point (P_S). The vector connecting the two piercing points gives the slip. The slip vector can be found both graphically and algebraically.

NOTE: Coloring the four dike segments (Dike A, North; Dike B, North; Dike A, South; Dike B South) in different colors and thoughtful labeling can help greatly in relating the map to the cross section.

EXAMPLE MAP AND CROSS SECTION



Solution for slip

Three planes can intersect in a point. An equation can be written for each plane, and if these equations are solved simultaneously, the coordinates of the point of intersection can be solved for.

We write the equation for a plane using the normal form for the equation of a plane. This equation states the distance "d" and direction from the coordinate origin to the plane. The distance is measured along a line normal to the plane (i.e., in the direction of the pole to the plane). The equation is written in vector notation using dot products: $\vec{n} \bullet \vec{v} = d$, where $\vec{n}$ is a unit vector normal to the plane, $\vec{v}$ is a vector that goes from the origin to the plane (any vector works), and d is the shortest distance from the origin to the plane *as measured in the direction of the unit normal vector; this distance can be either positive or negative*. The unit vector is described by its direction cosines (α, β, γ), and the vector $\vec{v}$ is given by the coordinates of a point on the plane.

Using the map and cross section, one could fill in the following table to get $\vec{n}$. Below I use the equations for x= north, y= east, and z = down from Lab 1 to get α, β, and γ.

Plane	Pole trend	Pole plunge	α	β	γ
Fault	0°	0°	1	0	0
Dike A (north)	90°	70°	0	0.3420	0.9397
Dike B (north)	90°	0°	0	1	0

Using the map, one can fill in the following table to get $\vec{v}$. This means measuring the coordinates of the points f (on the fault), a (on dike A), and b (on dike B).

Plane	Point	x (m)	y (m)	z (m)
Fault	f	0	20	0
Dike A (north)	a	20	0	0
Dike B (north)	b	20	40	0

In matrix form the vector equation for each plane are:

$$\vec{n}_F \bullet \vec{v}_F = d_F \quad or \quad \begin{bmatrix} \alpha_F & \beta_F & \gamma_F \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} d_F \end{bmatrix}$$

$$\vec{n}_A \bullet \vec{v}_A = d_A \quad or \quad \begin{bmatrix} \alpha_A & \beta_A & \gamma_A \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} d_A \end{bmatrix}$$

$$\vec{n}_B \bullet \vec{v}_B = d_B \quad or \quad \begin{bmatrix} \alpha_B & \beta_B & \gamma_B \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} d_B \end{bmatrix}$$

Using these equations, the information above for $\vec{n}$ and $\vec{v}$, one can calculate d for each plane. One can also measure d from the map *and/or the cross section* (again, d is the shortest distance from the origin to the plane, *as measured in the direction of the unit normal vector*; the sign of d depends on the direction of $\vec{n}$.

Plane	d (calculated)	d (measured)	Do they check?
Fault	0 m	0 m	Yes
Dike A (north)	0 m	0 m	Yes
Dike B (north)	40 m	40 m	Yes

We want to find the x,y,z coordinates (given by the column matrix X) of the point where the three planes intersect. To do this we solve for matrix X in the following matrix equation (compare this with those above):

$$\begin{bmatrix} \alpha_F & \beta_F & \gamma_F \\ \alpha_A & \beta_A & \gamma_A \\ \alpha_B & \beta_B & \gamma_B \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} d_F \\ d_A \\ d_B \end{bmatrix}$$

or

A X = B

In Matlab, all we need to do is use the following script (with the correct values for α, β, and γ):

```
% Matlab script lab14a.m
% Created 11/20/00
% Finds the intersection of three planes

% Set up direction cosine matrix A
% (it has direction cosines of the normals to the planes)
alphaF = 1.0000;      betaF = 0.0000;      gammaF = 0.0000;
alphaA = 0.0000;      betaA = 0.3420;      gammaA = 0.9397;
alphaB = 0.0000;      betaB = 1.0000;      gammaB = 0.0000;
A = [alphaF betaF gammaF; alphaA betaA gammaA; alphaB betaB gammaB];

% Set up distance matrix B
dF = 0;      dA = 0;      dB = 40;
B = [dF; dA; dB];

% Solve for the point of intersection
X = A\B
```

Using this procedure, we find the coordinates of the piercing point for the dikes on the north side of the fault, and they match the graphical answer from the cross section.

Plane	x (m)	y (m)	z (m)
North Piercing Point (calculated)	0	40	-14.6
North Piercing Point (measured)	0	40	-14.6

* Note that positive elevations have negative z-values

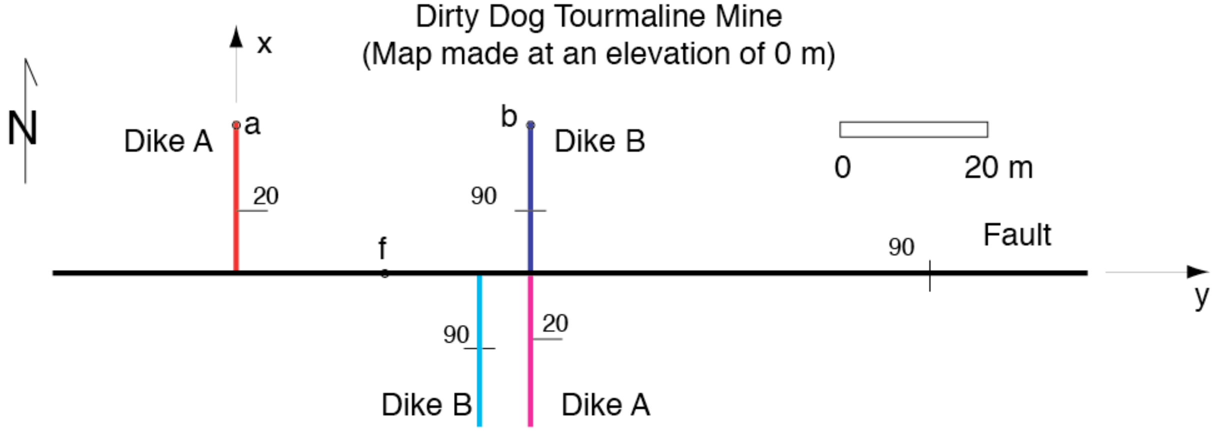
Repeating this procedure for the south side gives the second piercing point. From the two piercing points, one can find the slip vector.

Problem 2A: Graphical solution (**21 pts**)
Consider the fault on the map on the next page. The fault offsets two dikes. Consider all slip on the fault to have occurred after both dikes were intruded.

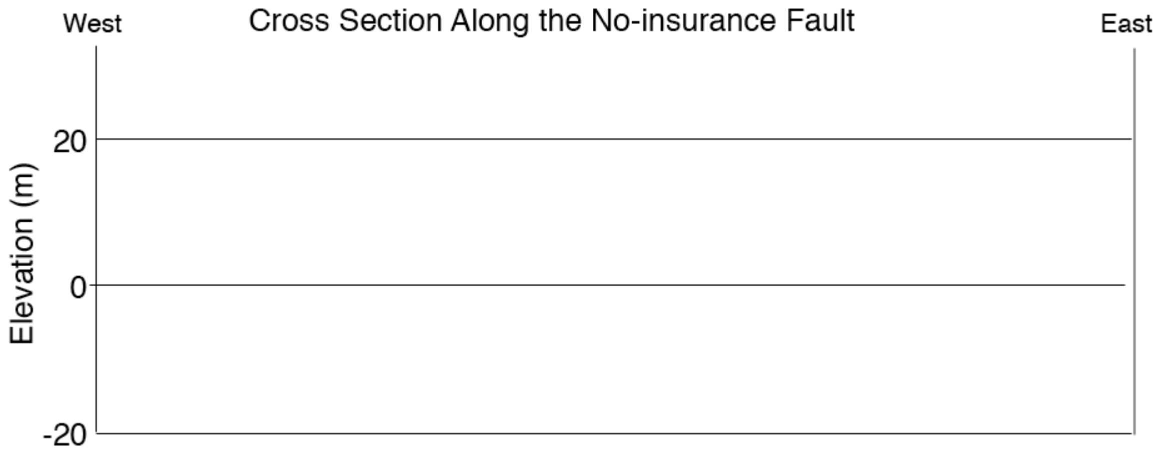
1 The **separation** of dike A in map view is: ____________________
(give the magnitude **(1 pt)** and sense [e.g., left-lateral or right-lateral] **(1 pt)**)
2 The **separation** of dike B in map view is: ____________________
(give the magnitude **(1 pt)** and sense [e.g., left-lateral or right-lateral] **(1 pt)**)
3 Prepare a cross section *drawn along the plane of the fault* that shows where the offset dikes *on both sides of the fault* intersect the fault; use the attached cross section. **(4 pts total)**
4 The dikes are very thin and can be idealized as planes. Two planes intersect in a (fill in the blank): _____________________**(1 pt)**
5 The feature formed by the dike intersection will intersect the fault plane at a point called a piercing point. Circle on your cross section the piercing point formed by the dikes on the north side of the fault, and label that piercing point "P_N". Then circle on your cross section the piercing point formed by the dikes on the south side of the fault, and label that piercing point "P_S", as in the example. **(3 pts; 1 pt for each circle, 1/2 pt for each label)**
6 Draw an arrow that goes from the upper piercing point to the lower piercing point. This gives the slip vector for this part of the fault. **(1 pt)**
7 The length of the slip vector is: (fill in the blank): ____________________**(1 pt)**
8 The trend of the slip vector is: (fill in the blank): ____________________**(1 pt)**
9 The plunge of the slip vector is: (fill in the blank): ____________________**(1 pt)**
10 Relative to the north side of the fault, the south side of the fault moved (circle all that apply): **(2 pts)**
Up Down East West North South

11 The sense of slip across the fault is (circle all that apply): **(3 pts)**
Right-lateral Left-lateral Dip-slip Normal Reverse Oblique
(Oblique slip is a combination of strike-slip and dip-slip)

Map of the No-insurance Fault and Offset Dikes
Dirty Dog Tourmaline Mine
(Map made at an elevation of 0 m)



Cross Section Along the No-insurance Fault



Problem 2B: Numerical solution **(39 pts)**

Two lines can intersect in a point. An equation can be written for each line, and these equations can be solved simultaneously to find the coordinates of the point of intersection.

Similarly, three planes can intersect in a point. If the equations for three planes are solved simultaneously, the coordinates of the point of intersection can be solved for.

How do we write the equation for a plane? The simplest way is to use the normal form for the equation of a plane. This equation states the distance "d" from the plane to the coordinate origin. This distance is measured along a line normal to the plane (i.e., in the direction of the pole to the plane). The equation is written in vector notation using dot products: $\vec{n} \bullet \vec{v} = d$, where $\vec{n}$ is a unit vector normal to the plane, $\vec{v}$ is a vector that goes from the origin to the plane (any vector works), and d is the distance. The unit vector is described by its direction cosines (α, β, γ) and the vector $\vec{v}$ is given by the coordinates of a point on the plane

Using the map and cross section, fill in the following table to get $\vec{n}$: Use the equations that have x=north, y=east, and z=down from Lab 1 to get α, β, and γ. **(1 pt/box =15 pts total)**

Table 2

Plane	Pole trend	Pole plunge	α	β	γ
Fault					
Dike A (north)					
Dike B (north)					

Using the map, fill in the following table to get $\vec{v}$. This means measuring the coordinates of the points f (on the fault), a (on dike A), and b (on dike B). **(1 pt/box = 9 pts total)**

Table 3

Plane	Point	x (m)	y (m)	z (m)
Fault	f			
Dike A (north)	a			
Dike B (north)	b			

In matrix form the vector equation for each plane are:

$$\vec{n}_F \bullet \vec{v}_F = d_F \quad or \quad \begin{bmatrix} \alpha_F & \beta_F & \gamma_F \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} d_F \end{bmatrix}$$

$$\vec{n}_A \bullet \vec{v}_A = d_A \quad or \quad \begin{bmatrix} \alpha_A & \beta_A & \gamma_A \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} d_A \end{bmatrix}$$

$$\vec{n}_B \bullet \vec{v}_B = d_B \quad or \quad \begin{bmatrix} \alpha_B & \beta_B & \gamma_B \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} d_B \end{bmatrix}$$

Using these equations, your information above for $\vec{n}$ and $\vec{v}$, find d for each plane. Then measure d from the map and/or cross section (again, d is the shortest distance from the origin, to the plane and the sign of d depends on the direction of $\vec{n}$). **(1 pt/box = 9 pts total)**

Table 4

Plane	d (calculated)	d (measured)	Do they check?
Fault	m	m	
Dike A (north)	m	m	
Dike B (north)	m	m	

We want to find the x,y,z coordinates (i.e., matrix X) of the point where the three planes intersect. To do this we solve for matrix X in the following matrix equation (compare this with those above):

$$\begin{bmatrix} \alpha_F & \beta_F & \gamma_F \\ \alpha_A & \beta_A & \gamma_A \\ \alpha_B & \beta_B & \gamma_B \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} d_F \\ d_A \\ d_B \end{bmatrix}$$

or

A X = B

Using the procedure in the example, find the coordinates of the piercing point for the dikes on the north side of the fault, and check your answer from the cross section. **(1 pt/box = 6 pts total)**

Table 5

Plane	x (m)	y (m)	z (m)
North Piercing Point (calculated)			
North Piercing Point (measured)			

The same procedure can be used to fine the piercing point on the south side of the fault, and by finding the distance and direction between these points the slip can be determined.

All the values in the table below match the values for the north side, so copy the values from Table 2 into Table 6 (no credit for table 6)

Table 6

Plane	Pole trend	Pole plunge	α	β	γ
Fault					
Dike A (south)					
Dike B (south)					

Using the map, fill in the following table to get $\vec{v}$. This means measuring the coordinates of the points f_s (on the fault), a_s (on dike A), and b_s (on dike B). The subscript s refers to points for the south side. **(1 pt/box = 9 pts total)**

Table 7

Plane	Point	x (m)	y (m)	z (m)
Fault	f_s (your choice)			
Dike A (south)	a_s (your choice)			
Dike B (south)	b_s (your choice)			

Now evaluate d **(1 pt/box = 9 pts total)**

Table 8

Plane	d (calculated)	d (measured)	Do they check?
Fault			
Dike A south)			
Dike B (south)			

Now find the coordinates of the south piercing point and check them against your cross section.

(1 pt/box = 6 pts total)

Table 9

Plane	x (m)	y (m)	z (m)
South Piercing Point (calculated)			
South Piercing Point (measured)			

<u>To get credit, include your Matlab scripts and your printout</u>!

Problem 3 **(10 points total)**

The purpose of this exercise is to introduce you to how a simple mechanical model can give insight into faulting processes. You have an opportunity here to “play” with a model that is not a “black box” and see how it behaves.

Using a 2-D screw dislocation model (see lecture notes) and the data from the 1906 San Francisco earthquake, estimate the average slip (to the nearest meter) and how deep the earthquake rupture extended (to ±5 km). To get started on this, copy lab14.m (see the bottom of my web page for GG303) into your GG303 directory and then type

help lab14

and then follow the directions. To run the code type

lab14(b,a)

where “b” is the slip across the fault and “a” is the depth of fault rupture. Include in your answer a copy of the printout with your best slip estimate, a lower bound for the rupture depth, an upper limit, and your best estimate (3 curves total).

```
function lab14(b,a)
% function lab14(b,a).  Draws a profile of predicted displacement at
% the ground surface as a function of distance from a long vertical
% strike-slip fault with constant slip using a screw dislocation model.
% Parameter "b" is the slip across the fault (in meters).
% The slip is TWICE the displacement on one of the fault walls!
% Parameter "a" is the depth of the lower edge of the dislocation (in km).
% Both parameters "b" and "a" must be placed between parentheses.
% For example, to start and just see the data type
% lab12(0,0)
% To get model curves you need to provide non-zero values for "b" and "a".
% If your curve is below the data, the slip and/or fault depth is too low.
% If your curve is above the data, the slip and/or fault depth is too high.
% Plots will be superposed.  To clear the screen to start over type
% clf
% The surface displacements are elastic displacements calculated
% using a screw dislocation solution (see lecture 23).
% The displacements are calculated along a horizontal plane
% that bisects a vertical screw dislocation in an infinite body.
% This dislocation extends from a depth of "a" km below the surface
% to "a" km above the surface.
% The horizontal plane represents the surface of a half-space,
% and here that is the ground surface.
% Slip across the dislocation results in no tractions on this
% plane (i.e., no normal and shear stresses act ON this plane),
% so the displacements on or below this plane are appropriate
% for those in the Earth around the central portion of a long vertical
% strike slip fault with a constant slip.
% Data for fault-parallel displacements (with error bars) are from the
% 1906 San Francisco earthquake as reported by Pollard and Segall (1987).
% The reference frame has the x-axis vertical and in the plane of the fault.
```

```
% The y-axis is normal to the fault and at the ground surface.
% The z-axis is horizontal and parallels fault strike.
% Estimate the slip to +/- 1 meter and the depth of faulting to +/- 5 km.

% Set the grid to calculate displacements on
y = 0:0.1:14;
x = zeros(size(y));


% Calculate displacement w parallel to the fault
w = (b/(2*pi)) * ( atan2(y,(x-a)) - atan2(y,(x+a)) );

% 1906 Displacement data
y6 = [0.18, 0.18, 0.18];       w6 = [2.05, 2.45, 2.87];
y5 = [0.50, 0.50, 0.50];       w5 = [2.11, 2.50, 2.91];
y7 = [1.48, 1.48, 1.48];       w7 = [1.69, 2.09, 2.50];
y4 = [3.65, 3.65, 3.65];       w4 = [1.43, 1.83, 2.23];
y3 = [3.92, 3.92, 3.92];       w3 = [1.38, 1.79, 2.19];
y8 = [5.72, 5.72, 5.72];       w8 = [1.15, 1.55, 1.95];
y9 = [6.40, 6.40, 6.40];       w9 = [0.97, 1.36, 1.79];
y10= [6.71, 6.71, 6.71];       w10 = [1.08, 1.48, 1.89];
y11= [6.82, 6.82, 6.82];       w11 = [1.28, 1.70, 2.10];
y12= [7.66, 7.66, 7.66];       w12 = [1.05, 1.45, 1.85];
y2= [11.26, 11.26, 11.26];  w2 = [0.60, 1.00, 1.41];
y1= [13.56, 13.56, 13.56];  w1 = [0.60, 1.00, 1.41];

% Plot 1906 data
figure(1)
plot  ( y6,w6,'-',y5,w5,'-',y7,w7,'-',y4,w4,'-',y3,w3,'-',y8,w8,'-',...
            y9,w9,'-',y10,w10,'-',y11,w11,'-',y12,w12,'-',y2,w2,'-',y1,w1,'-')
hold on
plot  ( y6(2),w6(2),'o',y5(2),w5(2),'o',y7(2),w7(2),'o',y4(2),w4(2),'o',...
            y3(2),w3(2),'o',y8(2),w8(2),'o',y9(2),w9(2),'o',y10(2),w10(2),'o',...
            y11(2),w11(2),'o',y12(2),w12(2),'o',y2(2),w2(2),'o',y1(2),w1(2),'o')

if b~=0
      % Plot model curve
      plot (y,w)
      aa = num2str(a);
      bb = num2str(b);
      text(y(100),w(100)+0.05,['a=',aa,' km, b=',bb,' m'])
end

xlabel('Distance from fault (km)')
ylabel('Displacement parallel to fault (m)')
title('1906 Displacements - Point Arena')
```