FAULT SLIP

I Main Topics

A Definitions of slip and separation

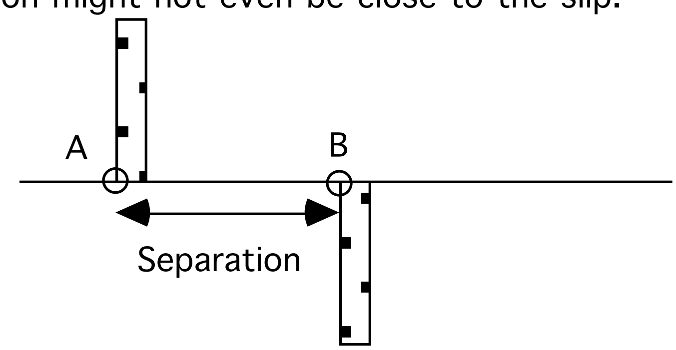
B Methods for determining slip

II Definitions of slip and separation

A Slip: The relative displacement of originally neighboring points on opposing walls of a fault (i.e., the relative displacement of piercing points). Slip on a fault typically is a maximum near the center of the fault and decreases to zero near the end of a fault.

B Slip vector: A vector connecting piercing points. It gives the direction and magnitude of slip. Slickenlines are inferred to parallel the slip vector. The slip vector typically will vary with position along a fault.

C Separation: The apparent offset of a feature as seen in a map view or a cross section. For example, distance AB below is the separation. Although points A and B lie on the same plane, they might not have been originally sited on the same line. As a result, A and B may not be piercing points and hence distance AB might not be the slip. In fact, the separation might not even be close to the slip.



If the slip vector parallels the intersection of an offset plane and a fault, the plane will appear unfaulted (e.g., consider a vertical dike offset by a vertical dip slip fault)

III Methods for determining slip at a point

A Find a line that originally extended across a fault

1 Stream channel

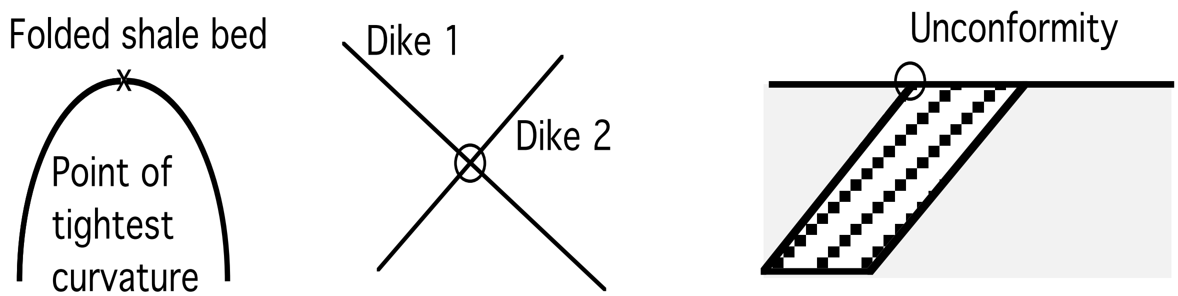
2 Lava flow/lava tube

3 Fold axis at a point on a folded bed

4 Intersection of planar features

a Intersection of two dikes

b Intersection of a bed at an angular unconformity



3 4a 4b

5 Methods for finding the orientation of lines at the intersection of planes

a Orthographic projection

b Cross product of normals to intersecting planes

c Plot intersection of planes on a stereonet

B <u>Locate piercing points on opposing walls of the fault</u>

(i.e., find intersections between a line and a fault plane)

1 Graphical solution

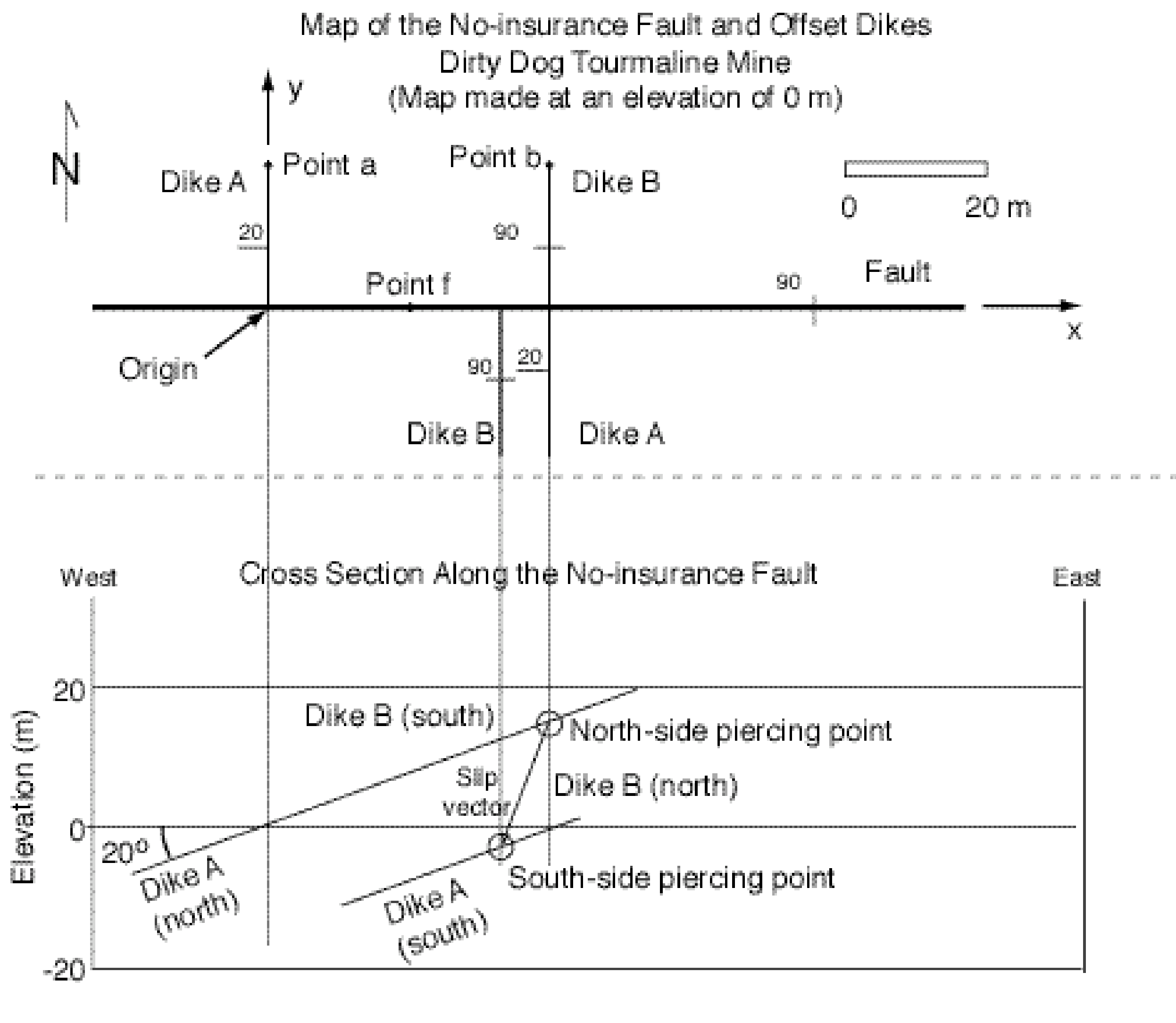
2 Solution of simultaneous linear equations for three planes

C <u>Determine the slip vector</u>

1 If P1 (x_1,y_1,z_1) and P2 (x_2,y_2,z_2) are piercing points, then slip vector **V** is $(x_1-x_2)\mathbf{i} + (y_1-y_2)\mathbf{j} + (z_1-z_2)\mathbf{k}\}$.

2 The length of V = $|\mathbf{V}| = \{(x_1-x_2)^2+(y_1-y_2)^2+(z_1-z_2)^2\}^{1/2}$

3 Unit vector along V = $\mathbf{V}/|\mathbf{V}| = \{(x_1-x_2)\mathbf{i} + (y_1-y_2)\mathbf{j} + (z_1-z_2)\mathbf{k}\}/|\mathbf{V}|$



D Solution of Simultaneous Linear Equations

Suppose two lines intersect in a point. An equation can be written for each line, and if these equations are solved simultaneously, the coordinates of the point of intersection can be solved for.

Similarly, 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.

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= east, y= north, and **z = up** from Lab 1 to get α, β, and γ.

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

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).

Plane	Point	x (m)	y (m)	z (m)
Fault	f	20	0	0
Dike A (north)	a	0	20	0
Dike B (north)	b	40	20	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, your information above for $\vec{n}$ and $\vec{v}$, find d for each plane. Then measure d from the map (again, d is the distance from the origin, and 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 (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

Linear algebra books always write AX=B

These equations could be solved using determinants and Cramer's rule. However, because many people solve simultaneous linear equations for a variety of reasons, many mathematical packages have been written to solve them. 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 = 0.0000;     betaF = 1.0000;          gammaF = 0.0000;
alphaA = -0.3420;    betaA = 0.0000;          gammaA = 0-0.9397;
alphaB = 1.0000;     betaB = 0.0000;          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, 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.

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

They check.

Lab 13

Problem 1 **(32 pts total)**

In the attached map for problem 1, a dike shows a left-lateral separation of 100m. The mapped surface has been eroded perfectly flat. Consider the four scenarios below:

Case A The marker unit is vertical
Case B The marker unit dips 20° to the east and the fault is a pure dip-slip fault.
Case C The marker unit dips 20° to the west and the fault is a pure dip-slip fault.
Case D The marker unit dips 45° to the west and the vertical component of slip is 200 m (north side up).

Questions

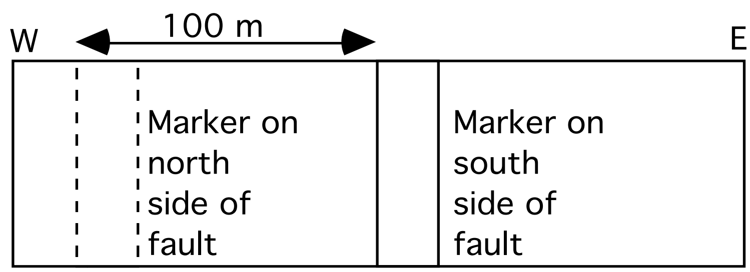
A What is the sense of slip? Dip-slip (north side up)? Dip-slip (south side up)? Left-lateral strike-slip? Right-lateral strike-slip? Oblique-slip? If the sense of slip can not be determined uniquely, state the possible options. Be as specific as you can.

B What is 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 can not be determined, state that.

C What would you expect for the trend, plunge, and rake of slickenlines on the fault?

	Question A	Question B	Question C
Case 1	2pts	Horizontal_____1 Vertical_______1 Net__________1	Slickenside trend:_______________ 1 Slickenside plunge:______________ 1 Slickenside rake (relative to east):___ 1
Case 2	2pts	Horizontal_____1 Vertical_______1 Net__________1	Slickenside trend:_______________ 1 Slickenside plunge:______________ 1 Slickenside rake (relative to east):___ 1
Case 3	2pts	Horizontal_____1 Vertical_______1 Net__________1	Slickenside trend:______________ 1 Slickenside plunge:______________ 1 Slickenside rake (relative to east):___ 1
Case 4	2pts	Horizontal_____1 Vertical______1 Net__________1	Slickenside trend:______________ 1 Slickenside plunge:______________ 1 Slickenside rake (relative to east):___ 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 **(14 pts total) DON'T DO THIS PROBLEM!**

A pure strike-slip fault in the Fanta Sea offsets the vertical Great Gold vein, but the strike of the fault is unknown (see attached map for Problem 2). Find the slip on the fault for the strikes listed in the table.

Strike	Amount of Slip (S)
N45°W	2 pts
N0°E	2 pts
N45°E	2 pts
θ (an arbitrary strike)	5 pts

** Hint: To solve for the slip for a fault of arbitrary strike, first solve for the slip S in terms of the distance D and the angle Ψ, and then solve for Ψ in terms of θ_{fault} and θ_{vein}.

Questions

Is the slip greater for faults that strike to the northwest or the northeast for the northeast-striking vein? Why? Hint: Use your answer to the 5-point question to help you.

____2 pt___

Does the position of the fault affect the amount of slip you calculate, or is the orientation of the fault (relative to the dike) the key factor? Why?

____1 pt___

Problem 3A: Graphical solution (**21 pts**)
Consider the fault on the attached page (map for Problem 3). 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 page to prepare your cross section.
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 with an "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 with an "S". **(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 Assuming the north side of the fault is fixed, 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)

Problem 3B: Numerical solution **(39 pts)**

Two lines 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= east, y= north, and **z = up** from Lab 1 to get α, β, and γ. **(1 pt/box =15 pts total)**

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)**

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 (again, d is the distance from the origin, and the sign of d depends on the direction of $\vec{n}$). **(1 pt/box = 9 pts total)**

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

Linear algebra books always write AX=B

Those of you who remember determinants and Kramer's rule from an earlier math class could solve the equations that way. However, because **many** people solve simultaneous linear equations for a variety of reasons, many mathematical packages have been written to solve them. In Matlab, all we need to do is use the following script (with the **correct** values for α, β, γ, dF, dA, and dB):

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

% Set up direction cosine matrix A
alphaF = 0.0000;     betaF = 1.0000;      gammaF = 0.0000;
alphaA = 0.3420;     betaA = 0.0000;      gammaA = -0.9397;
alphaB = 1.0000;     betaB = 0.0000;      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, 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)**

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.

Problem 4 **(10 points total)**
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 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')
```

Problem 5 **(47 pts total)**

Answer the following questions, assuming that the Puddingstone fault was active only during Eocene time and the dikes are of late Cretaceous age (see the map for Problem 5).

4A) What are the attitudes of the features on the maps? Make sure to give the direction of dip!

Feature	Strike	Dip
Fault	2pts	2pts
Puddingstone/chalk contact	2pts	2pts
Dike A	2pts	3pts
Dike B	2pts	3pts
Dike C	2pts	3pts

4B) What planar feature intersects each of the three dikes to yield three lines of intersection that can be used to determine piercing points on the fault? **5 pts**

____

4C) What is the trend and plunge of these lines that are offset by the fault?

Trend: 1 pt	Plunge: 1 pt

4D) What is the relative displacement (i.e., slip) for each of the dikes? **(9 pts total)**

Dike	Amount of slip (m)	Sense of slip
A	2pts	1pt
B	2pts	1pt
C	2pts	1pt

4E) Why doesn't the puddinsgstone/chalk contact appear to be offset when both the puddingstone and the chalk are cut by the fault? **(3 pts)**

____

____

____

4F) Which side of the map is closer to an end of the fault? What is your evidence? **(3 pts)**

____

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____

____

4G) Why might the landslides be located where they are (i.e., why might the ground be weak there)? **(2 pts)**

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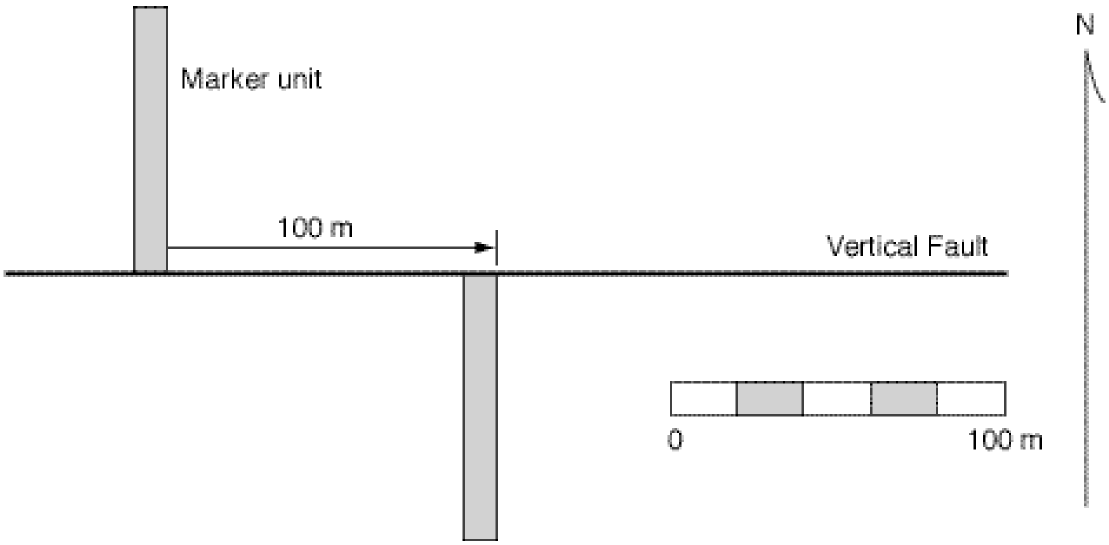
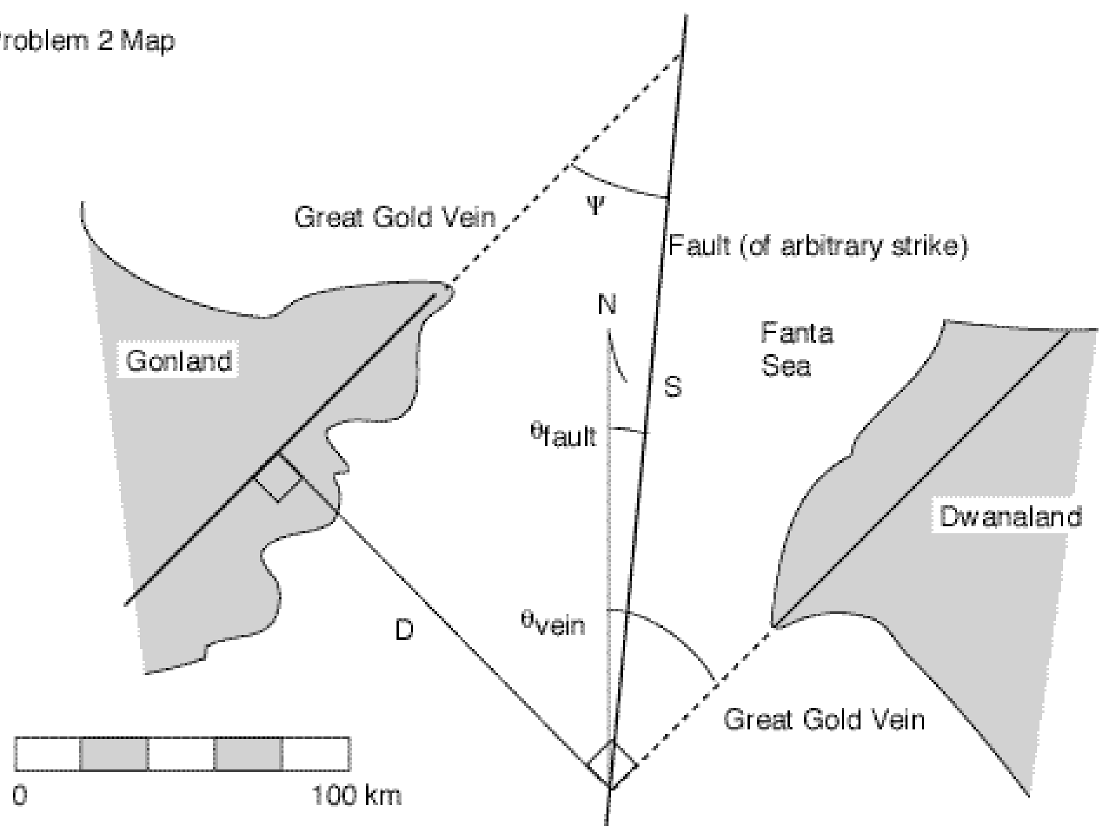
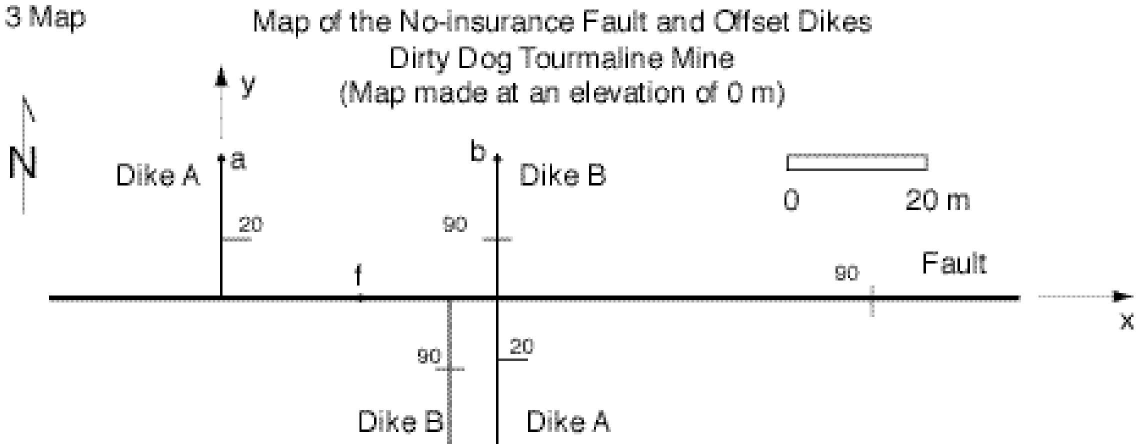
Problem 1 Map

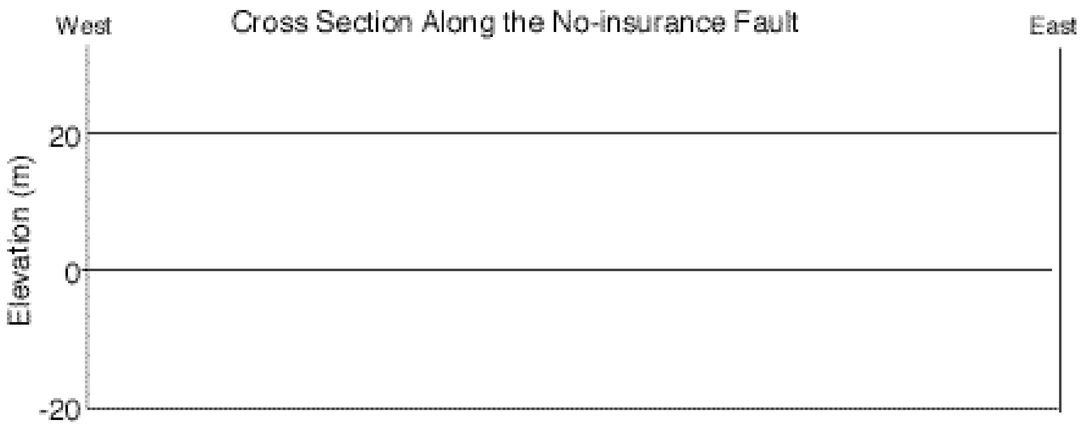


Problem 2 Map



Problem 3 Map





Problem 5

Geologic Map of the Caprock Plateau Area
by Psi Kottic
11/3/95