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SCIENTIFIC NOTEBOOK #136

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Robert Terhune

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Initial Entries Apr 17, 1995

Task 1: Computer Calculations of Dike/Fault interaction

Principal Investigator: Robert Terhune Robert Terhune

Calculations by: Robert Terhune RWT

Scope of work

Define the conditions under which an upward-propagating dike would be captured by an intersecting fault. The new calculations are to be based on the results of the earlier calculations that suggested complete capture by an 80 degree dipping fault that is intersected by a vertical dike at depths of 300 and 1000 meters. The calculation for the 60 degree dipping fault intersected by the dike at a depth of 1000 meters suggested that the magma could both intrude the fault and continue to move vertically upward as a vertical dike.

The calculation to be performed under this scope of work are to better define the conditional depth and fault dip for which capture of the dike would be complete, partial, or absent. It is desirable that the region between the intersection depth and the surface be modeled in some of the calculations. The fault dip and depths are indicated in the following table

Dip / Depth	30 degree	40 degree	50 degree	60 degree	70 degree	80 degree
300m	Task 1	Task 1	Task 1	Task 1	Task 1	1993
1000m.	Task 1	Task 1	Task 1	1993	Task 1	1993
2000m	Task 1	Task 1	Task 1	Task 1	Task 1	Task 1

Table 1 Calculation parameters of dip vs depth.

The calculations are to be done in a sequence designed to eliminate unnecessary depth-dip combinations. All calculations will initially be with the rock properties used for the previous 1000 m calculations. If time and money remain after the above series of calculations have been completed a second series will be started using a different set of physical properties.

The results of the calculations as they proceed will be discussed with the CNWRA staff on a biweekly basis. A final report on the calculations will be issued on completion of the work for task 1.
End of Scope of Work

Special training: None
End of Special training

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Hypothesis to be evaluated:

It is assumed that for a propagating dike that intersects a fault, there is some dip angle of the fault for a given intersection depth that the magma will move up the fault instead continuing to propagate the dike fracture. The purpose of this study is to model the propagation of the dike fracture and determine under what conditions the dike will continue past a fault and/or open up the fault as a function of dip angle and depth of intersection.

End of Hypothesis to be evaluated.

Summary of the technical approach used in the analysis

Develop a computer model of a geologic section that incorporates an equation of state for the rock, the overburden stress, a dipping fault, the potential path of a dike, and models the propagation of the dike fracture. The computer code to be used for this analysis is DYNA3D.

DYNA3D is a explicit finite element code for analyzing the transient dynamic response of three dimensional solids and structures developed and maintained by Methods Development Group, Mechanical, Engineering Department, of the Lawrence Livermore National Laboratory, Livermore, CA.

Summary of the technical approach used in the analysis

Brief description of
Assumptions:

Assumptions are made with respect to

1. Defining the problem as a plane strain problem
   See below
2. The form of the overburden stress
   See Item 2 after Calculational Plan
3. The boundary conditions
   See below
4. Effects of magma heat on equation of state model.
   See Item 4 after Calculational Plan
5. The physics of dike propagation.
   See Item 5 after Calculational Plan

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Assumption for Plane strain geometry.

Pollard (See references) describes the geometry of a generalized dyke based on numerous studies as being on the order of several meters thick, several kilometers in outcrop length, and several kilometers in depth. The displacement of the dyke wall is essentially normal to the orientation of the fracture so it seemed a reasonable approximation to model the dyke as a, mode I, blade crack in plane strain. Creating a 3D model that would give results different from a plane strain model requires modeling significient variation of the crack geometry in the plane of the dyke crack. This would add new variables and complications to the problem which would not contribute to the primary goals of this task, In addition the size of the problem would be "n" times the size of the plane strain problem where n is the number of zones in the plane of the dyke crack. Consenquently, the plane strain approximation is not only within accepted practice for the purposes of this analysis but neccessary to achieve the results with a reasonable effort.

End of Assumption for Plane strain geometry.

Initial/boundary conditions

The grid is approximately 1700 m in the vertical y direction, 2000 meters in the horizontal x direction and 20 meters in the horizontal z direction.

The global boundary conditions are as follows

Boundary	Boundary condition
x = xmin	no displacement in x direction
x = xmax	no displacement in x direction
y = ymin	no displacement in y direction
y = ymax	free surface or transparent boundary
z = zmin	no displacement in z direction
z = zmax	Plane of symmetry

The dike lies on the x=0 plane and expands in both the positive and negative x direction.

The fault is normal to the x-y plane.

End of Initial/boundary conditions

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Reference documents

1. Robert Whirley and J. O. Hallquist. "DYNA3D A Nonlinear, Explicit, Three-dimensional Finite Element Code for Solid and Structural Mechanics: User Mahual" UCRL-MA-107254, May 1991
This reference for the DYNA3D computer code gives a complete description of the code, the assumptions incorporated in the model, and includes descriptions the equation of state models, and the boundary conditions available as well as other aspects of the model.

2. David D. Pollard. "Elementary Fracture Mechanics Applied to the Structural Interpretation of Dykes". Geol. Assoc. Can Spec. Pap., 34, 5-24, 1987
This reference discusses the fracture mechanics of dyke propagation with respect to fracture configuration and stress state.

3. John R Lister and Ross C. Kerr. "Fluid-Mechanical Models of Crack Propagation and their Application to Magma Transport in Dykes". Jour. of Geophysical Research. Vol 96, No. B6 Pages 10049-10077, June 10, 1991
This reference discusses the stresses involved in dyke propagation, the level of neutral buoyancy (LNB) and how it affects the propagation of the dyke, and the shape of the dyke fracture during propagation.

4. R. G. Van Buskirk. D. S. Gardiner, S. W. Butters. "Characterization of Yucca Flat Materials. Terra Tec Inc. University Research Park 420 Wakara Way Salt Lake City, Utah. 84108 TR 78-67 November 1978
This reference give the mechanical test data for samples obtained from drill holes at depths that vary from 500 to 1000 meters. The data used was on Dolomite Limestone samples from hole U7ae and Ue7ns. This was the same material used in the previous study at a depth of 1000 m.
End of References

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Identify

(a) Configuration management is maintained by the Lawrence Livermore National Laboratory.

(b) Computer platform used: SUN 3

(c) Directory and file names
1. Sensitivity studies
   a. Dikeparm, EOS
   b. Dikeparm, Dikezone
   c. Dikeparm, DikeLen
   d. Dikeparm, Pres
   e. Dikeparm, Vel
   f. Dikeparm, dip90
2. Calculations
   a. Depth300m, dipXX
   b. Depth1000m, dipXX
   c. Depth2000m, dipXX

where XX varies from 30 to 80 in steps of 10 degrees

(d) Computer language and compiler:
1. Language: Fortran 77
2. Compiler: Sun3 Fortran 77 Compiler

Identify aspects affecting computational reliability.

Sensitivity studies were done to evaluate the following:

(a) Balance of zone size on accuracy of calculation vs time step. Goal is to use a zone size where the results vary slowly with zone size but the time step of a reasonable size that the calculation will complete in a reasonable amount of time.

(b) The sensitivity of the calculations to the length of the pressurized dyke for a given dyke pressure.

(c) The effect of assuming the magma heat will make the rock more ductile, and more compressible by vaporizing the water within the rock near the dyke wall.

(d) The sensitivity of the calculational results on the velocity of the magma front.

(e) The sensitivity of the calculational results on the magma pressure for a given dyke length.

(f) The effect of a fault on the dike fracture propagation rate.

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Primary references used for theoretical analysis

1. Overburden stress:
   (a) J.C. Jaeger and N.G.W. Cook
   "Fundamentals of Rock Mechanics"
   Chapman and Hall, London. 1971
   (b) J.C. Jaeger
   "Elasticity, Fracture and Flow"
   Barnes and Noble, New York. 1956
2. Effect of magma heat on dyke wall
   (a) S.P. Clark Jr.
   "Handbook of Physical Constants"
   The Geological Society of America, 1966

Brief description of DYNA3D computer code.

The DYNA3D global model is built from blocks. Each block has its own finite element grid, material properties, initial conditions and boundary conditions. For this study the 8 node continuum elements are used for the finite elements of the blocks. The blocks are put together to form a global model with one coordinate system and where the exterior boundary conditions of the blocks form the global boundary conditions. The blocks are tied together by a slip surface that links each node of one block boundary to the boundary of the block other and visa versa. One side is designated as a master slip and the other is designated as the slave. It is important that the slave side has the same or more nodes than the master so that the slave can follow the deformations of the master.

Stresses, strains, displacements and any wave form will transmit across a tied slip as though the blocks were one. There are a number of different types of slips that can be used between blocks. For this study three slip types will be used. These are

(a) tied slip to lock two blocks together
(b) sliding with separation and friction used for the fault
(c) tied with failure used for the dyke

Type (b) requires both a static and kinetic friction coefficient to be specified. Type (c) require both a shear stress failure limit and tensile failure limit to be specified.

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Description of DYNA3D continued

Other type of boundaries used for this study are sliding boundaries along a specified plane, non-reflecting (transmitting) boundaries, symmetry planes, free surfaces, and prescribed pressure history on a boundary. We had planned to use non-reflecting boundaries for all exterior global boundaries but realized that this study is essentially a quasi-static problem, not a wave propagation problem, and not suitable for a non-reflecting boundary condition. Consequently the sliding boundaries along a specified plane was used where the displacement is restricted in the direction normal to the plane. A prescribed pressure history was used to model the expansion of the dyke walls and the magma front propagating the crack toward the surface.

There are a number of methods of defining the gravity stress initialization. We chose to use the method where the hydrostatic pressure at a given depth is the integration of the density of the rock from the surface to the specified depth. This integration is done for each element in each block at time equal zero.

End of Description of DYNA3D

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Calculational Plan

1. Establish the units to be used in DYNA3D and the reports.
2. Establish method for determining the overburden stress.
3. Define the material properties and equation of state.
4. Estimate effect magma heat might have on rock EOS.
5. Assumptions on physics of dyke propagation.
6. Sensitive studies
   - a. Sensitivity of results to variation in rock shear strength
   - b. Sensitivity of results to different compression models
   - c. Sensitivity of results to Zone size
   - d. Sensitivity of results to Dike Length
   - e. Sensitivity of results to magma velocity
   - f. Sensitivity of results to magma pressure
   - g. Sensitivity of results in approximation to fault. dip = 90
7. Design block structure to form fault/dyke system. One of our goals is to make all calculations the same except for the variables of dip and depth. Since the previous calculations varied from one calculation to the other, the calculations done in 1993 will be recalculated for this study.
   - a. Intersection depth at 300 meters. Surface is ymax. = 0
     1. dip = 80 degrees (different EOS for 1993 calc)
     2. dip = 60 degrees
     3. dip = 30 degrees
     4. dip = 50 degrees
     5. dip = 70 degrees
     6. dip = 40 degrees
   - b. Intersection at 1000 meters. Same block structure as above for each dip angle except ymax at depth of -700 m.
   - c. Intersection at 2000 meters. Same block structure as above for each dip angle except ymax at depth of -1700 m.
8. Run calculations for intersection depth at 300 meters for dip angles of 80, 60 and 30 degrees
9. Run calculation for intersection depth at 2000 meters for dip angles of 80, 60 and 30 degrees.
10. Run rest of calculations in order based on results of these six calculations.

end of plan

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1. Establish the units to be used in DYNA3D and the reports. DYNA3D will accept any set of consistent units. The following units were used for this study

Parameter	Units	Abrev.
Distance	meters	m
Time	miliseconds	ms
Mass	Megagrams	Mg
Force	Giga-Newtons	GN
Stress	Giga-Pascal	GPa
Energy	Giga-Joules	GJ
density		Mg/m^3
velocity		m/ms
acceleration		$m/(ms)^2$

The gravity constant in these units is

$$1 \text{ g} = 9.80 \text{ e-06 } m/(ms)^2$$

2. Establish the method for determining the instu overburden stress.

Assuming that no horizontal displacement takes place at depth then the model for the principal stresses T_i at depth is:

$$T_1 = d*g*h$$

$$T_2 = T_3 = (pr/(1-pr))*T_1$$

where

d = rock density
g = gravity constant
h = depth from the surface
pr = Poissons Ratio

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Overburden stress continued. . .

if the assumption is made that an additional horizontal stress exists in the direction of the second principal stress then

$$T_1 = d*g*h$$

$$T_2 = (pr/(1-pr))*T_1 + T_0$$

$$T_3 = (pr/(1-pr))*T_1 + pr*T_0$$

Another assumption is that the stresses become hydrostatic due to action of creep over long periods of time. The principal stresses at depth under this assumption are

$$T_1 = T_2 = T_3 = d*g*h$$

$$P_0 = .333*(T_1 + T_2 + T_3)$$

$$P_0 = d_r * g*(y-y_0)$$

where

P_0 is the overburden pressure

d_r is the density of the rock

g is the gravity constant = 9.8 e-06 $m/(ms)^2$

y_0 is the ground surface = 0.0

There is no convincing data to select one model over the other as while there seem to be considerable data showing horizontal stresses equal to the vertical stresses there is many cases where the horizontal is either less than or greater than the vertical stress. Since the hydrostatic model is the simplest model, it was chosen for the insitu stress model.

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3. Define the material properties and Equation of State.

The rock type simulated in the model is Dolomite Limestone and is the same as was used in a previous study. The equation of state is based on laboratory tests on small samples taken from cores obtained in hole U7ae and hole Ue7ns located in the Yucca Flats area of the Nevada Test Site. The samples of Dolomite Limestone came from a depth of 869 m (U7ns) and 610 m (Ue7ae). The measured characteristic properties of the Dolomite Limestone are as follows:

Bulk density	= 2.69 Mg/m^3
Dry density	= 2.64 Mg/m^3
Grain density	= 2.84 Mg/m^3
Ultrasonic Sound velocity	= 6.13 m/ms
Ultrasonic Shear velocity	= 3.19 m/ms
Water by weight	= 2.0 %
Calculated porosity	= 0.220
Calculated Poissons Ratio	= 0.314
Calculated Bulk Modulus	= 58. GPa
Calculated Shear Modulus	= 26. GPa

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Rock Equation of State Measurements

The equation of state tests were done on small core samples taken from hole Ue7ae and Ue7ns at the Nevada Test Site. The rock was classified as Dolomite Limestone. Cylindrical shaped samples approximately 6.4 cm in height and 3.2 cm in diameter are normally cut from the most competent portions of the core for all the compression tests.

The compression test that form the basis of the data used in this report are: the hydrostatic compression tests to pressures of 0.4 GPa, the uniaxial strain tests to an axial stress of 0.4 GPa, and the triaxial compression failure tests at confining stresses of 0.0, 0.05, and 0.4 GPa. In each test the axial stress compressed the height of the sample and the confining stress compresses the diameter of the sample. The associated strains with these stresses are the axial strain and the transverse strain respectively. It is how these two stresses vary in relation to each other that defines the type of test.

The hydrostatic compression test: The axial stress and confining stress are increased equally such that all stresses are equal at all times. Measurements of the stress state and the transverse and axial strain are taken at regular intervals of axial stress

The uniaxial strain test: The axial stress is first compressed a small amount which causes the diameter of the sample to expand. The confining stress is then increased till the transverse strain is zero. Measurements are taken of the axial stress, the confining stress and the axial strain at regular intervals of axial stress. This is repeated sequentially where each time the transverse strain is compressed back to zero. This test is very efficient in squeezing out the porosity of the sample at low compression.

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Equation of state continued. . . .

The triaxial compression failure tests: The axial stress and the confining stress are set to a given value that defines the stress state of the test. The axial stress is then increased till the rock sample fails while the confining stress remains constant at the initial value. Measurements of the axial and transverse strain, and the stress state are made at the failure stress. The volumetric strain usually will dilate as the sample approaches failure because of micro fractures that are opening under the stress load.

The equation of state parameters consist of two curves, one that relates the compression pressure to the volumetric strain and the other relates the shear failure stress to the mean pressure. See EOS data plots. The data for the volumetric strain vs pressure is shown below. Note that 1 kilobar = 0.1 GPa.

Pressure (kb)	Relative volume change= $(v-v_0)/v_0$	
	Hydrostate	
0.0	0.0	
0.32	0.0013	
1.00	0.0035	
2.00	0.0062	
3.0	0.0085	
4.0	0.0106	
	Uniaxial Strain	
	Loading	Unloading
0.0	0.0	0.0064
0.120	0.00295	0.0076
0.290	0.0060	0.0090
0.495	0.0084	0.0100
0.720	0.0103	0.0112
1.000	0.0116	0.0124
1.465	0.0139	0.0140
2.0	0.0157	0.0157
3.0	0.0184	0.0184
4.0	0.0210	0.0210

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EOS data continued:

There are two pressure - volumetric strain curves, one from the hydrostatic pressure tests and one from the uniaxial strain tests. The EOS data plots shows the volumetric compression data for the hydrostatic stress and uniaxial, strain tests. The initial bulk modulus for the hydrostatic test is 27.3 GPa and for the uniaxial strain test the modulus was 4.9 GPa. At 0.4 GPa the bulk modulus was 43.5 GPa for the hydrostatic test and 42.5 GPa for the uniaxial strain test indicating that it is the matrix of the rock that is being compressed although the sample in the hydrostatic test contains approximately 1% more void space than the sample in the uniaxial test. This is approximately the same bulk modulus as determined from the ultra sonic measurements. The initial data is given in kilobars and positive strain in compression.

The shear stress data is from both the triaxial and uniaxial laboratory measurements. The data for the shear stress is given below in kilobars. Note 1 kb = 0.1 GPa

Confining stress (kb)	Shear stress (kb)
drill hole Ue7ns depth 1999 feet	
0.0	0.60
0.5	2.5
4.0	5.5
drill hole U7ae depth 2850 feet	
0.0	0.66
0.5	1.24
4.0	7.5

The EOS data plots also show the stress difference, the axial stress minus the confining stress, as a function of the mean stress at failure for triaxial failure tests. In addition the path of the stress state for the uniaxial strain test is also shown. Since the range of stresses for all of the calculations is much less than 0.3 GPa, only the low stress portion of the data is relevant.

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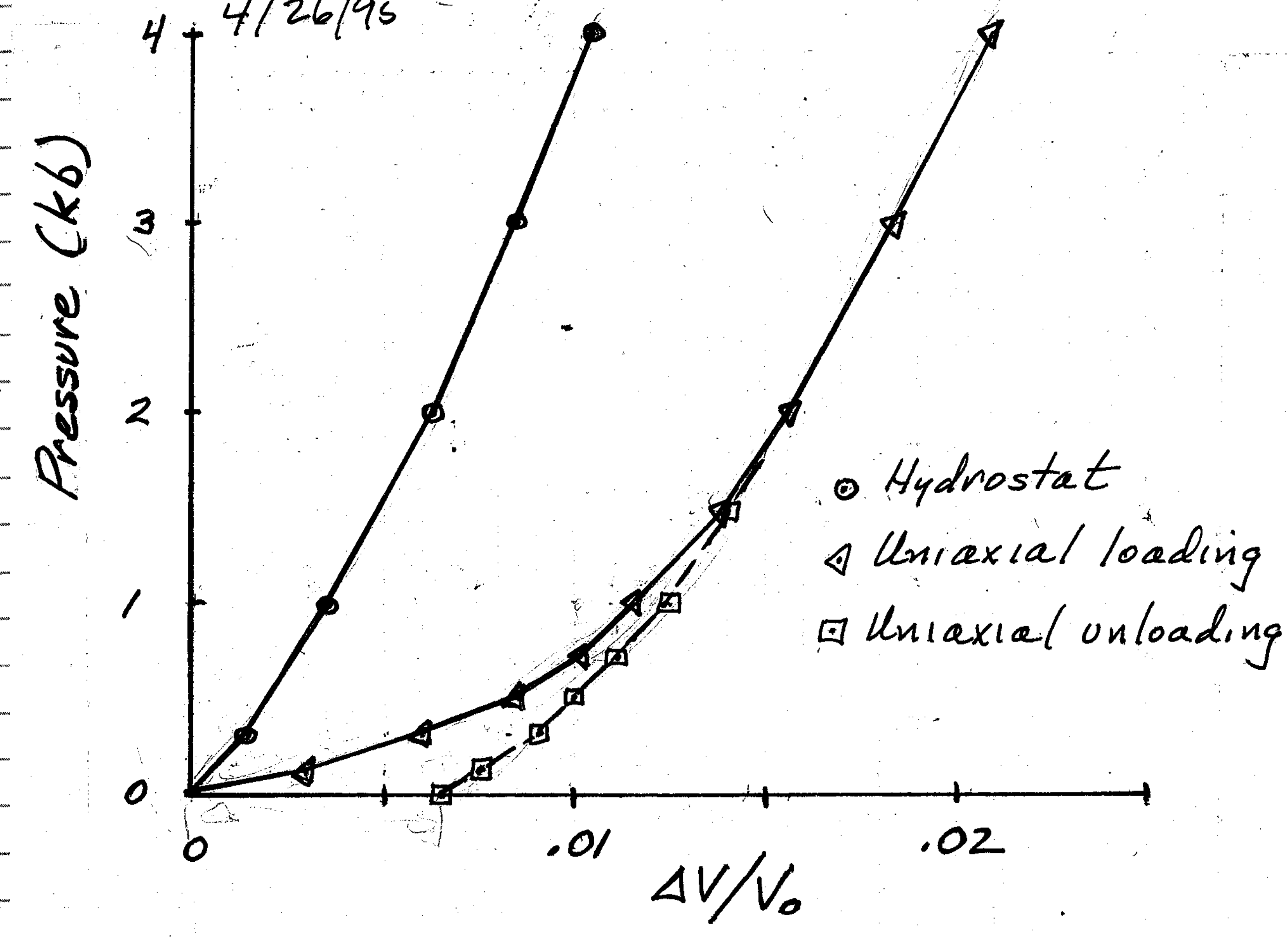

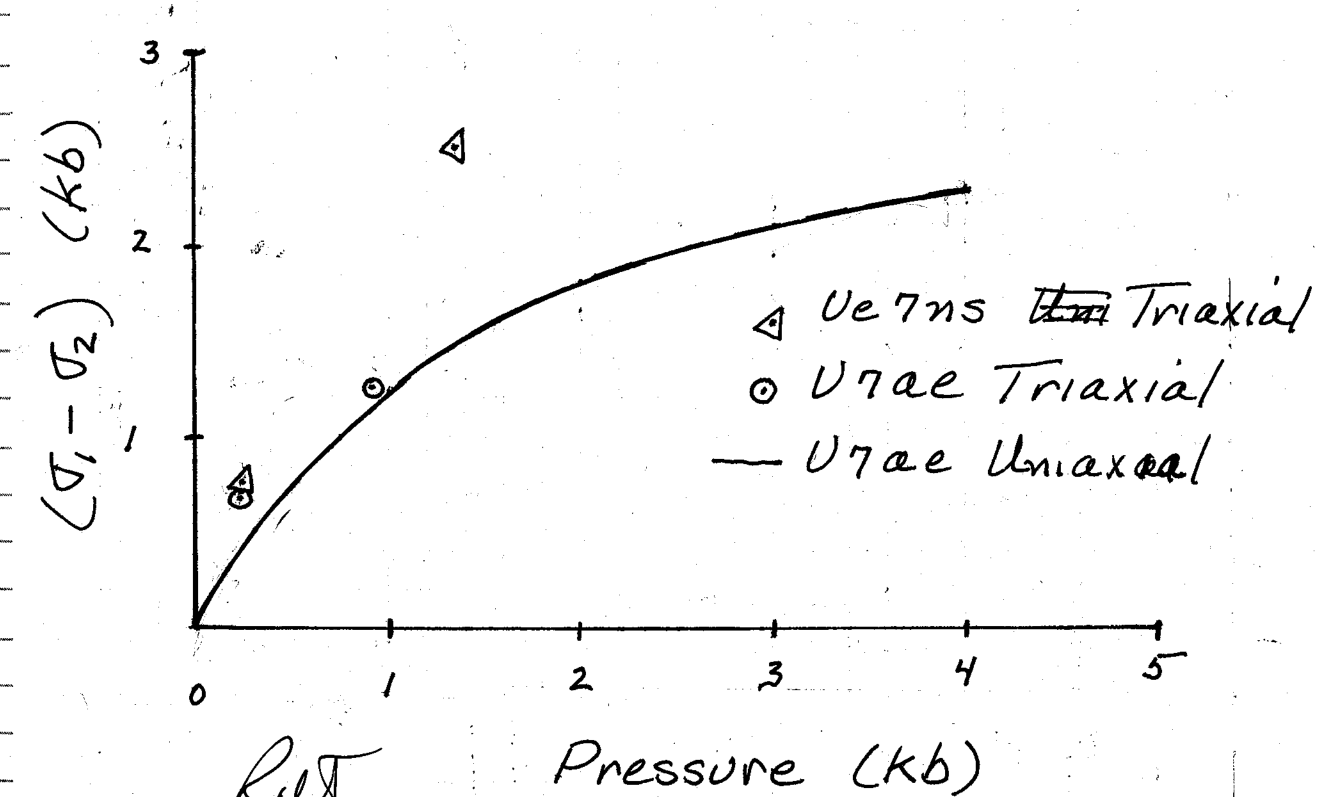

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EOS data continued:

The data from hole u7ae is in approximate agreement with the shear stress path observed in the uniaxial strain tests. The maximum shear stress for the uniaxial tests were 0.24 GPa.

In a tensile test the most tensile stress is increased to the point that the rock fails in a brittle manner which determines the tensile strength of the rock. Most rocks are relatively weak in tension because of inherent flaws. When data from tensile tests are not available as in this case, the tensile strength is usually estimated by extrapolation of the triaxial failure envelope from the unconfined compressive strength point to where it intersects the pressure axis. For the Dolomite Limestone this approach gives a tensile strength of that varies between 0.02 to 0.03 GPa depending on which data set us used.

4. EOS data as used in the calculations

The equation of state data used in the calculations requires the data be in the form of pressure vs volumetric strain. The volumetric strain = $\ln(v/v_0)$ where v_0 is the initial volume. The pressure is in GPa.

Pressure (GPa)	Strain = $\ln(v/v_0)$
Hydrostate	
0.0	0.0
0.03	-.0013
0.10	-.0035
0.20	-.0061
0.30	-.0085
0.40	-.0106
1.00	-.0200
Uniaxial Strain	
0.0	0.0
0.03	-.0005
0.06	-.0061809
0.08	-.0087615
0.10	-.01014
0.13	-.011929
0.18	-.013903
0.23	-.015873
1.03	-.029559

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The shear strength is entered into the model as a equation where

$$(\sigma_1 - \sigma_2)^2 = 3(a_0 + a_1 * p + a_2 * p^2)$$

where a_0, a_1, a_2, and the tensile strength pc are specified Two strength curves were specified and tested for suitability.

Case 1	a_0 = 0.0012	a_1 = 0.038
	a_2 = -.001	pc = -.031
Case 2	a_0 = 0.0003	a_1 = 0.009
	a_2 = 0.0	pc = -.033

Strength curve Case 1 models the low pressure triaxial tests and merges into the uniaxial strain data. Strength curve Case 2 is an estimate of the strength at high temperature and is about half the strength of Case 1.

5. Equation of State Assumptions

The effect of the magma on the side of the dyke may decrease the rock's strength in two ways. (1) The rock contains about 2% water by weight. The heat from the magma causes the water to pressurize the pores and microfractures in the rock causing failure at a much lower shear stress. (2) Adding heat to a rock will increase the ductility of all rocks. However the increase in ductility can for some rocks increase the ultimate strength and for others lower the ultimate shear strength as compared to the cold rock of these laboratory tests. The temperature of basaltic lava's have been observed in the range of 1000 to 1250 degrees centigrade. Some dolomite and limestone data show a decrease in strength. Data for Limestone (densities 2.60 to 2.71 Mg/m^3) exists for temperatures to 800 degrees centigrade and when extrapolated to 1100 degrees centigrade indicate compressive strengths less than 0.1 GPa. Data for Dolomite (density 2.82 to 2.87 Mg/m) show a decrease in strength to a range of 0.025 to 0.4 GPa. from a failure strength of 0.8 GPa at 24 degrees centigrade. See page 26 for figure RWT 5/5/95

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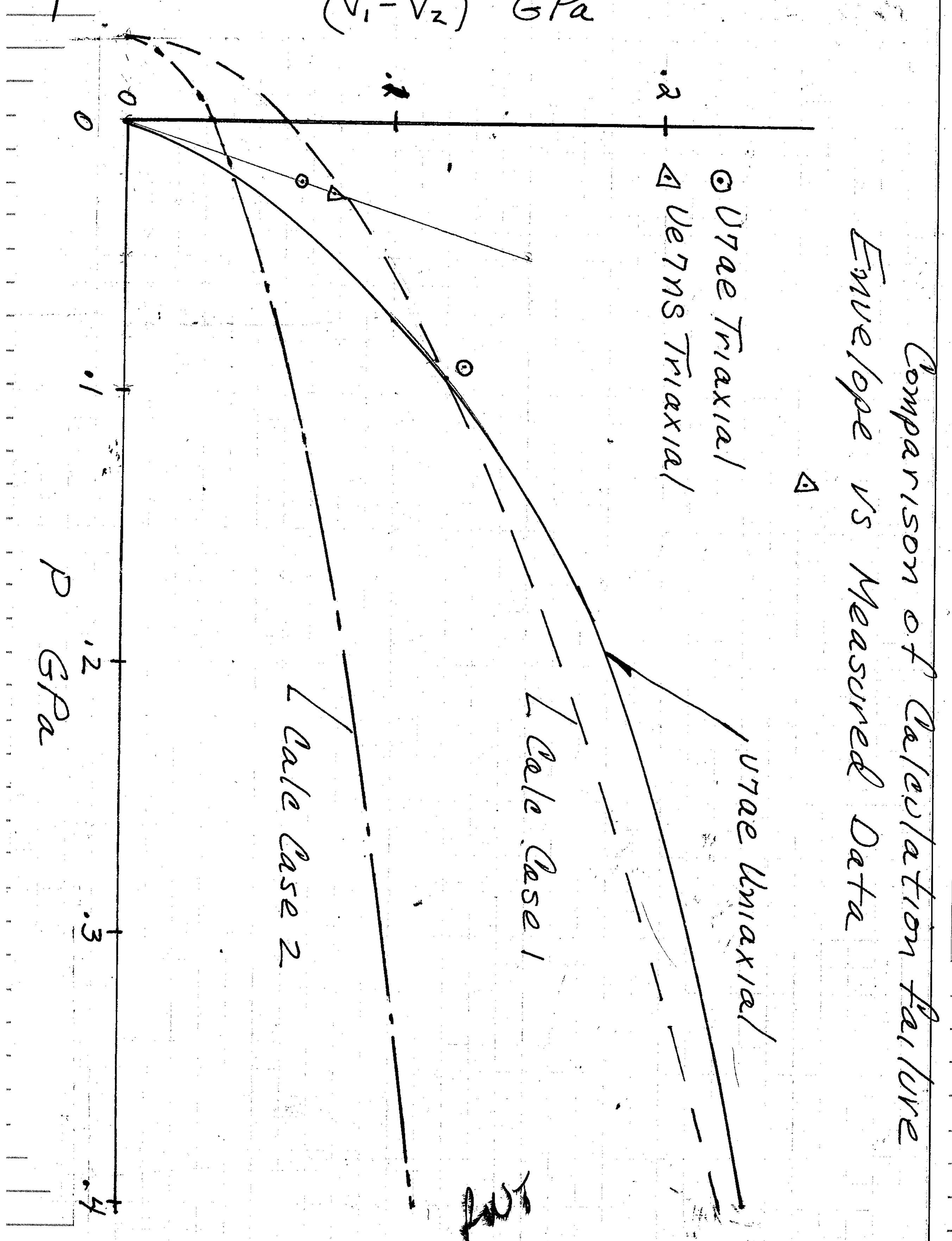

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Equation of State Assumptions continued:

In addition to the magma effects on the strength there is a small sample effect where the most competent portion of the core is tested and inherent fractures which exist in larger blocks of rocks are not represented in the data. All of these effects would weaken the rock below that measured on the samples. Based on these considerations two strength curves were developed where one matched the U7ae triaxial strain and uniaxial data (#1) and the other was half the first one (#2). The ~~low~~ high RWT shear strength curve (#2) was used for most of the sensitivity studies. A ductile model was used except for tensile failure.

The heat of the magma may also effect the compressibility of the rock where the water vapor from the rock escapes into the dyke fissure allowing the pressure to collapse the pores space. In other words the rock becomes more compressible without the water than with the water in the pores.

Based on the above logic, the more compactable compressibility curve of the uniaxial stress test is favored over the hydrostat however a sensitivity study between the two is presented.

5. The physics of dyke propagation

The physics of dykes formation is controversial and data is limited to seismic observations of magma fracture of the rock, from lava flow around volcanos and mid ocean ridges, and field studies of dykes exposed by uplift and erosion. This data indicates that magma fracture occurs at velocities less than 1 m/s and with typical widths that vary between 0.5 to 5 m and outcrop lengths that vary between 1 to 10 km. Seismic velocities indicate that the melt initially collects in reservoirs at the base of the lithosphere. Pressure induced expansion of a reservoir will create tensile hoop stresses in the surrounding rock leading to fractures oriented, normal to the least compressive regional stress through which the magma can propagate. According to Lister the primary driving force for a magma driven fracture is the buoyancy of the magma in the host rock. At shallow depths, where the buoyancy is negative, the magma may still drive the fracture due to the reservoir pressure and/or momentum of the magma.

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Lister argues that the total effective pressure p_t in the magma is given by

$$p_t = p_h + p_e + p_f + p_v + p_0 + \text{const}$$

where

- p_e is the pressure due to elastic deformation of the wall
- p_h is the hydrostatic pressure
- p_v is the viscous pressure drop from viscous magma flow.
- p_f is the pressure required to fracture the rock
- p_0 is the overpressure between the magma and the rock.

The elastic stress is given by modules of elasticity times the strain. The strain is approximated by w/L where w is the half width of the fracture and L is the shorter of the other two dimensions of the fracture. The modulus of elasticity can be either Youngs modulus, the bulk modulus or the shear modulus to give a ball park estimate of the elastic stress in the rock.

$$p_e = m*w/L = k* \text{ dyke wall displacement}$$

where

- m is the modulus of elasticity
- w is the width of the fracture
- L is the length of the fracture
- k is a proportional constant for a given media

The hydrostatic pressure of the magma on the surrounding rock is in neutral buoyancy if the density of the magma equals the density of the rock. The buoyancy is positive if the magma is less dense than the rock and negative if the magma is more dense. The pressure is given by

$$p_h = (d_m - d_r)*gz$$

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where

- d_m is the density of the magma
- d_r is the density of the surrounding rock.
- g is the gravity
- z is a measure of the depth

The estimated Reynolds number for magma flow in dykes is much less than 1000 indicating the flow is laminar. For laminar flow the viscous pressure drop is approximated by

$$p_v = v*h^2 /(w^2 *t)$$

where

- v is the viscosity of the magma
- h is the height of the fracture
- w is the width of the fracture
- t is the time since fracture initiation

The fracture stress is often characterized by a fracture toughness coefficient that includes the effect of microfractures in the rock surrounding a propagating crack. The internal pressure required for the propagation of a magma fracture is given by

$$p_f = K/(L)^{1/2}$$

where

- K is the fracture toughness coefficient
- L is a characteristic length of the crack

The internal pressure of the magma must expand the fracture against the tectonic stress normal to the crack to allow the magma to flow. The overpressusre is difference between the magma internal pressure and the tectonic stress given by

$$p_0 = p_i - s_r$$

where

- p_i is the magma internal pressure
- s_r is the tectonic stress normal to the crack

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RWT 5/4/95

Lister argues that if the dyke is to remain open at its lower margin then the magma internal pressure p_0 must be at least comparable to p_h. If the dyke does not propagate upward then $p_0 + p_h$ must be less than p_f. Thus for a stationary dyke p_h must be much less than p_f.

Estimated values of the parameters for a stationary dyke indicate the maximum height is on the order of 100 m and the maximum width is on the order of 2 mm. A stationary dyke is very thin such that the magma would freeze and would not propagate. Consequently since known dykes are approximately 1 meter in width, their height must be much greater than a 100 m. As the height increases, p_h increases and p_f decreases. Thus when the height is much much greater than 100 m then p_f is much less than p_h, indicating that the pressure required to fracture the rock ahead of the crack is much less than the available stress to drive the fracture. This suggests that the rate of propagation of the crack is not controlled by the resistance to fracture but by the resistance of the viscous flow up the dyke to the crack tip. Lister argues that by assuming p_h is approximately equal to p_e then the following relationship holds for the region of the crack far back from the tip.

$$h^2 / w = 7. e{+}06 \text{ m}$$

Since w is on the order of one meter and h is on the order of several thousand meters, then the above ratio is much greater than 7. e+06 m which suggests that p_h is much greater than p_e.
The dominate stresses left which are involved in the propagation of the magma are the viscous pressure and the hydrostatic pressure where

$$p_v = p_h.$$

RWT 5/4/95

The Physics of Dyke Propagation continued

The half width w_0 of the crack in this region is proportional to the viscosity, the flow rate of the magma, and the buoyancy of the magma. Near the crack tip the overpressure and hydrostatic pressure must drive the walls of the crack back against the elastic resistance of the surrounding rock and regional stress. Lister solves the equations for elastohydrodynamic flow for the shape of the crack behind the tip. The results of this analysis indicates that a bulb forms near the crack tip where the half width is greater than the half width far back of the tip. When the crack toughness is assumed to be zero the half width of the bulb near the tip is 1.27* w_0 .
Pollard investigated dyke propagation from the point of view of fracture mechanics. The dyke was modeled as a blade shaped mode I elastic crack.
A magma pressure P was assumed sufficient to dilate the crack against a remote compressive stress S and the elastic stiffness of the rock. The change in the elastic strain energy is given by

$$U = \textbf{pi}*a^2 *(P-S)^2 \, [(1-pr)/(2*\textbf{shr})]$$

where
- a is the half length of the crack
- P is the magma pressure
- S is a compressive stress the crack is opening against
- pr is Poissons Ratio
- **shr** is the elastic shear modulus
- **pi** is 3.14...

The energy available for fracture is given by the change in strain energy with respect to crack length.

$$G = - \,\mathbf{d}U/\,\mathbf{d}a$$

resulting in the energy available for a increment of propagation at each of the two dyke tips of

$$G = \textbf{pi}*a*(P-S)^2 \, [(1-pr)/(2*\textbf{shr})]$$

RWT 5/4/95

The Physics of Dyke Propagation continued

An estimate of the stress difference (P-S) is obtained from comparing the equation for displacement at long range from a dyke to measurements of displacement on several volcanos. Assuming range for the shear modulus is 1 < **shr** < 6 GPa and a Poissons Ratio 0.25, the driving pressure falls in the range of

.001 GPa < (P-S) < .004 GPa

If one assumes a rock stiffness closer to those measured on laboratory samples, a driving pressure of 20 to 30 MPa would result. Thus

.020 GPa < (P-S) < .030 GPa

Pollard discusses what he calls a "Cohesive Zone Model" as shown on next page. The cohesive zone model. Magma pressure, P, is exerted on the dyke wall except over a small length L at the dyke tip. This length of dyke wall may be subject to a fluid pressure P_L

This model resembles the conditions of the proposed Dyna3d calculations.

The stress intensity factor K is given by

$$K = (P-S)*(\mathbf{pi}*a)^{1/2} - P*(8*L/\mathbf{pi})^{1/2}, \qquad L \ll a$$

where

- a is the half length of the crack
- P is the magma pressure
- S is a compressive stress the crack is opening against
- L is the unpressurized dyke wall

Setting K to zero and solving for L gives the distance ahead of the magma that the stress intensity would be reduced to zero.

$$L = (\mathbf{pi}^2\ a/8)*[(P-S)/P]^2$$

RWT 5/4/95

The Physics of Dyke Propagation continued

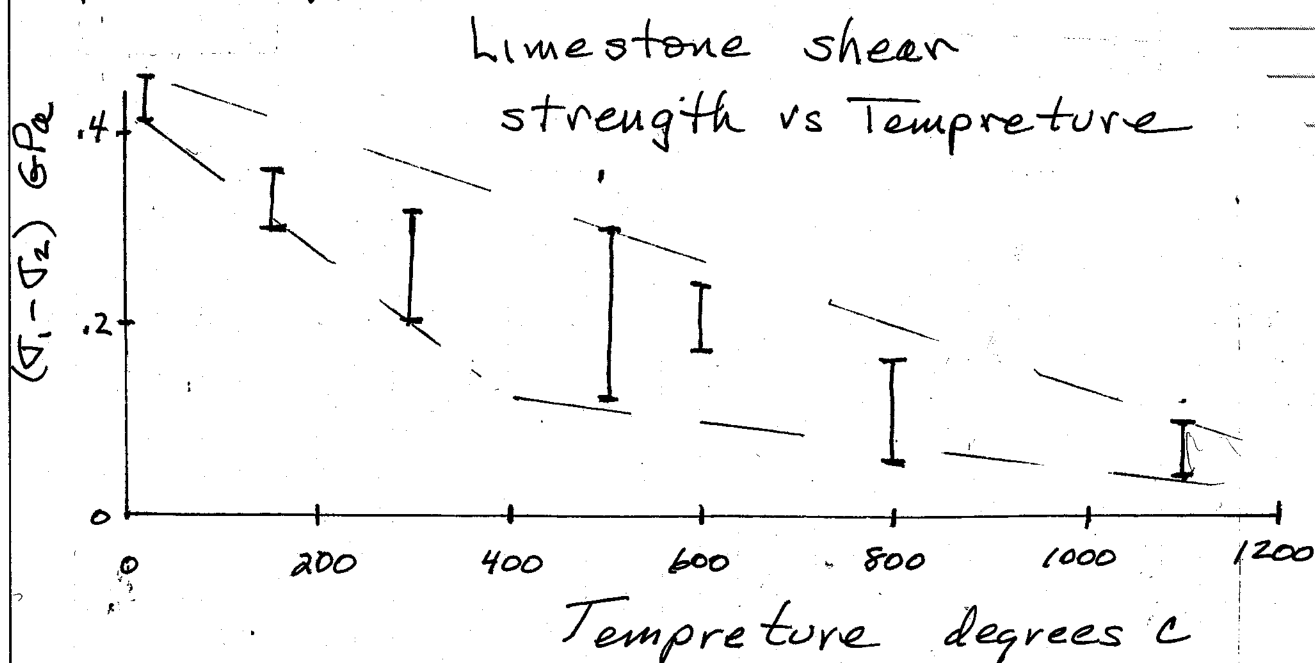
Assuming that the ratio of (P-S)/P is on the order of .3 and the crack half length is on the order of 600 m then the crack tip leads the magma pressure by

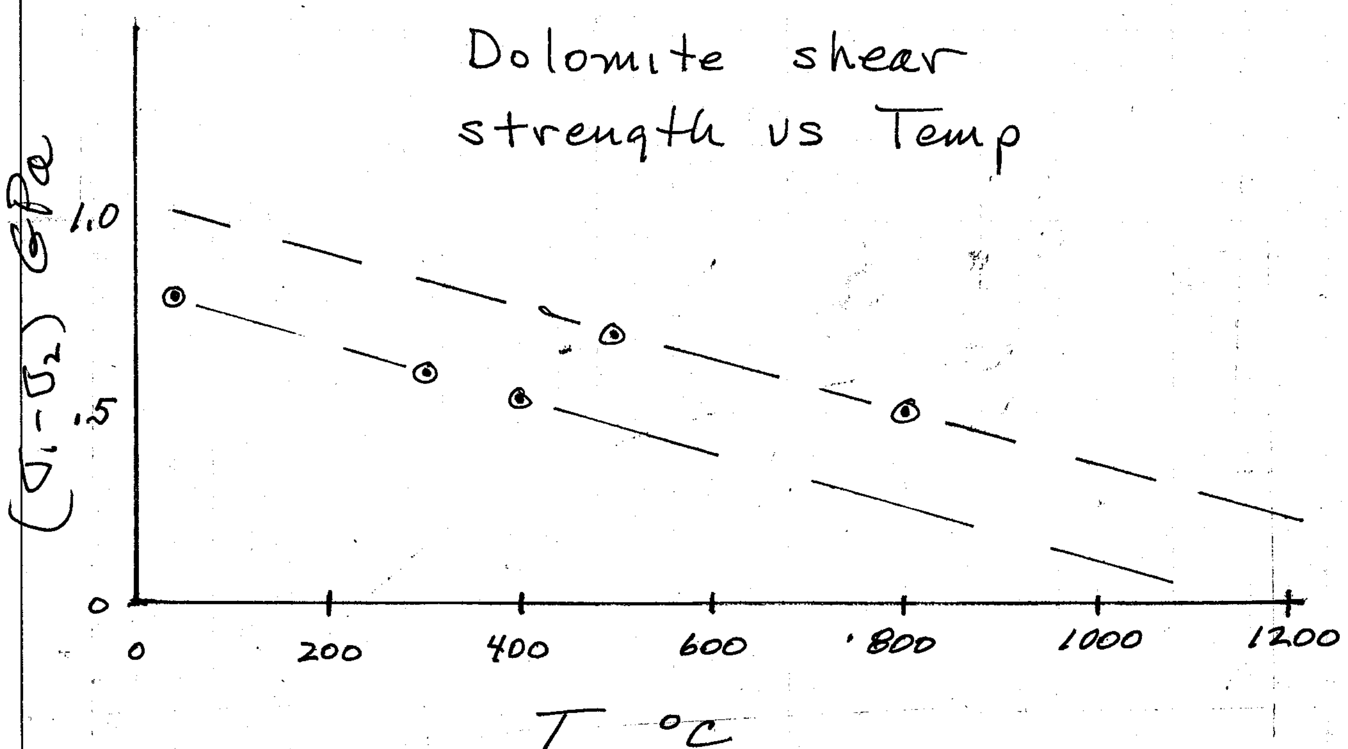
L = 80 m

End "Physics of Dyke Propagation"

RWT

RCT 5/8/95





5/8/95

Sensitivity studies for EOS.

Set up four calculations

#	shear strength curve id.	Compressibility Curve	pr (GPa)	Initial Crack Tip depth (m
1	CASE 1	uniaxial	0.03	-460
2.	CASE 2	uniaxial	0.03	-460
3	CASE 1	hydrostatic	0.03	-460
4	CASE 2	hydrostatic	0.03	-460

The grid for each calculation extended from a depth of -1700 m to the surface. The zone size was 20 m. The dyke was tied from the surface to a depth of -460 m and open from -460 m to -1700 m. The dyke surface pressure "pr" was set at 0.03 GPa which a test calculation show that for the uniaxial compresibility the displacement is approximately 0.5 m. The dyke pressure was applied only to the open part of the dyke.

Results

#	Disp of Dyke Well (m)	Crack Tip depth (m)	Unpressureized Dyke Length
1	0.448	-410	50 m
2	0.448	-410	50 m
3	0.265	-370	90 m
4	0.265	-370	90 m

At dyke pressure of 0.03 the strength curve does not effect the results. This means the stress stays elastic and below the strength shear stress of CASE 2. The uniaxial allows greater ~~strength~~ that displacement of the dyke wall and less distance of the crack tip from the pressurized region.

5/8/95

The results ~~of~~ agrees with "Pollard" as discussed ~~by~~ on page 24/25 where L = 80 @ pr ≈ 0.03 is bracketed by the calculational results of L = 50 & L = 90 m.

Decided to run 2 additional calculations to determine what pressure is required to give 0.5 m dyke wall displacement using both strength curves.

$$pr = .03 \times \frac{.5}{.265} = 0.056$$

#	Shear Curve	Compressibility Curve	pr	Crack tip
5	CASE 1	hydrostatic	0.056	-460
6	CASE 2	hydrostatic	0.056	-460

Results

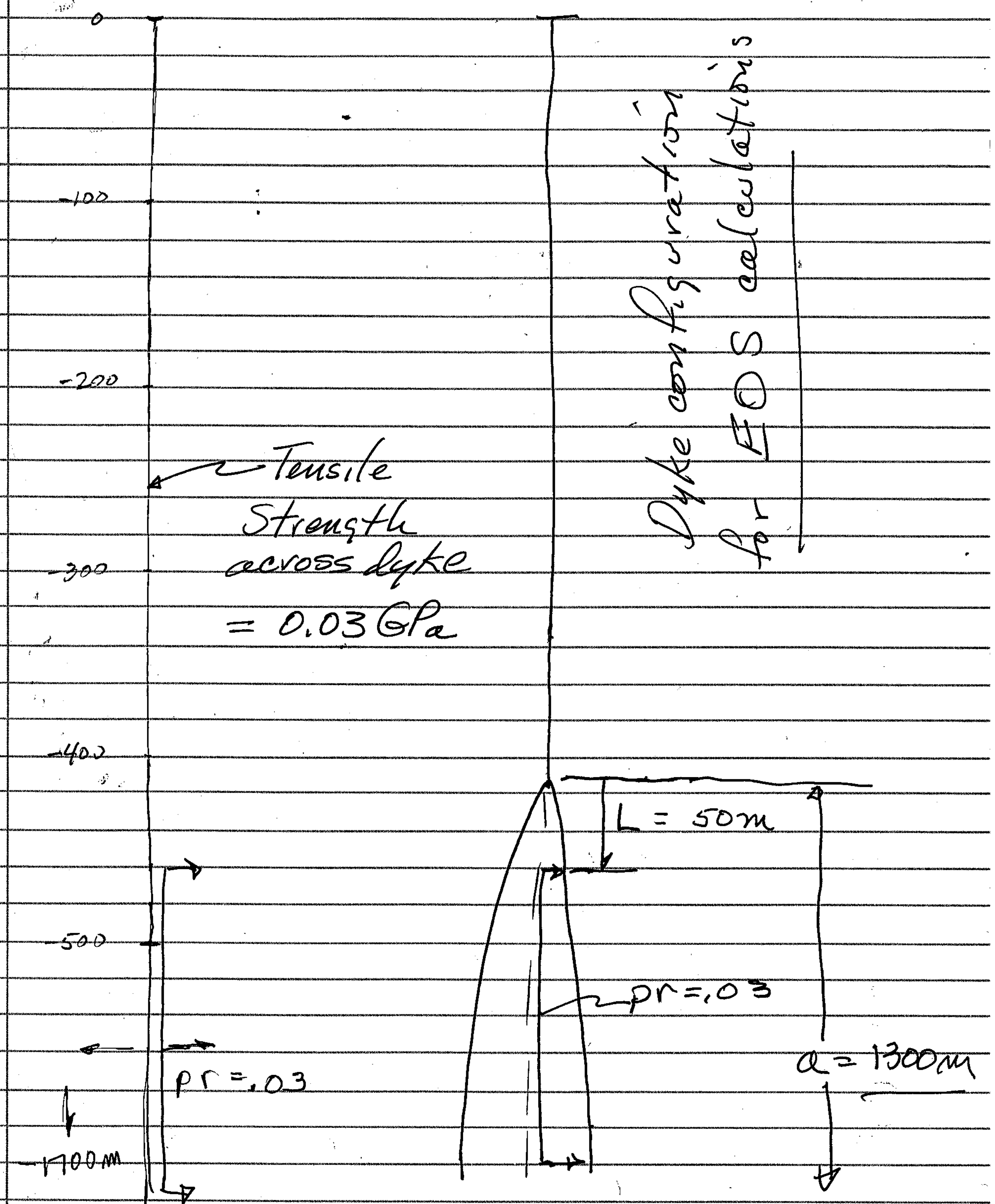
#	Disp (m)	Crack tip	Unpressurized Crack Length
5	0.438	-250	210 m
6	3.41	-270	190 m

For calc #6, the low strength curve, the higher dyke pressure caused the dyke walls to yield plastically. The displacement increased to 3.41 m, almost a order of magnitude increase over the elastic solution. The high strength curve gave the elastic solution.

* Decision. Calculations will use the uniaxial compressibility curve and the high strength curve so that the calculations remain in the elastic region.

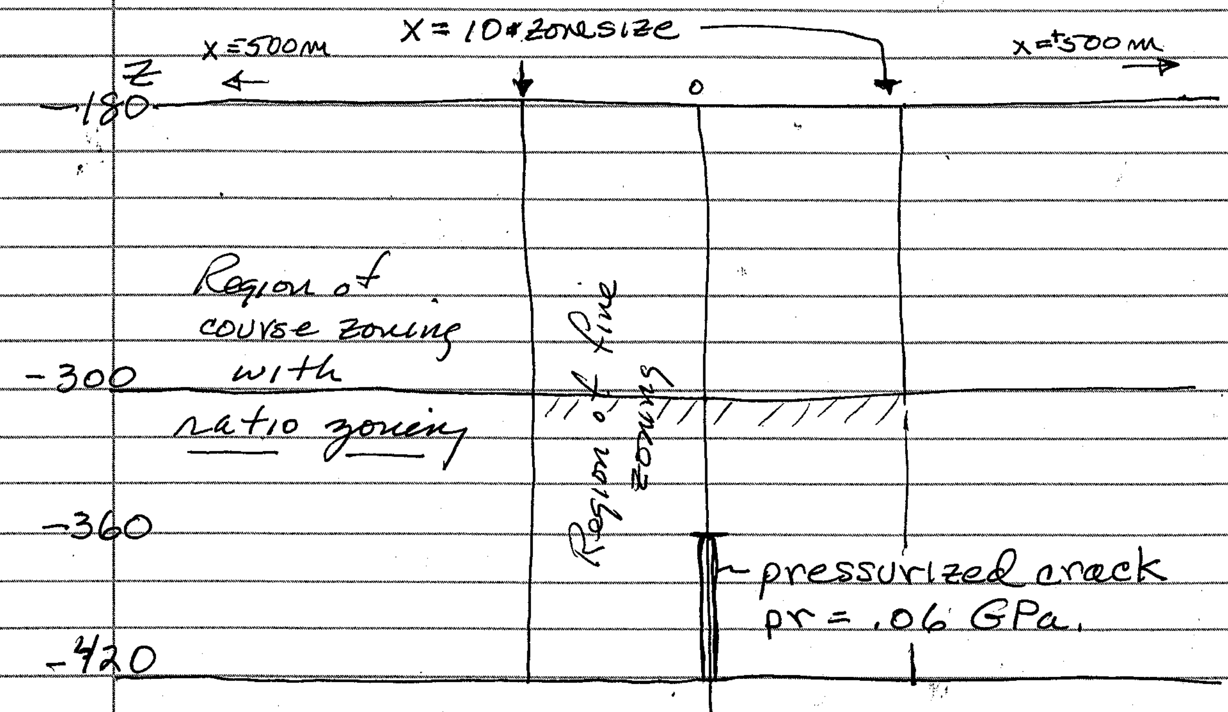
5/8/95

yet give a displacement of 0.5 m with a dyke pressure in agreement with "Pollard" estimates -



5/9/95
Sensitivity study on zone size

Setup four calculations to determine the sensitivity of the results to zone size. The measure for the sensitivity will be the parameters of dyke growth. These are crack half width and tip growth beyond the pressurized region.
The grid for the calc were as follows



Course zone size = 2 * fine zone size

Problem #	fine zone size	Course zone size	Δt (msec)
1	5.0	10.0	.501
2	2.5	5.0*/10.0	.250
3	10.0	20.0	.980
4	20.0	20.0	1.780

* Region next to dyke above -300m

The EOS was case 1 for strength and the uniaxial compression curve

5/9/95 Results of zone size calc

Calc 1 zone size = 5.0 m

Time	disp	crack tip	L
0.5	±.183	-235	125
1.0	±.194	-215	145
1.5	±.195	-215	145
2.0	±.195	-215	145

Calc 2 zone size = ~~10.0~~ 2.50 m

Time	disp	crack tip	L
0.5	±.188	-200	160
1.0	±.195	-200	160
1.5	±.197	-200	160
2.0			

Calc 3 zone size = 10.0 m

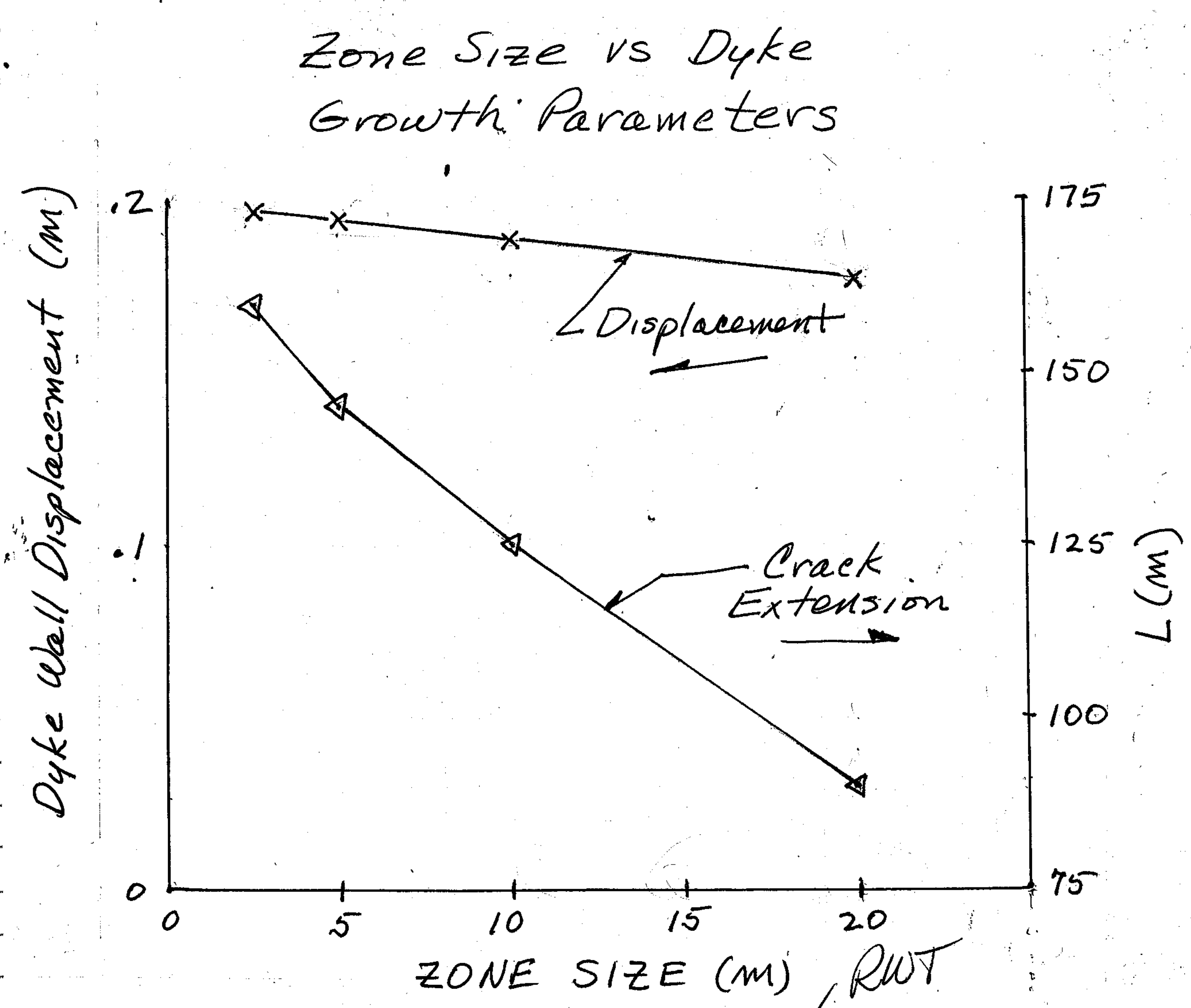
Time	disp	crack tip	L
0.5	±.178	-255	105
1.0	±.188	-235	125
2.0	±.188	-235	125
3.0	±.189	-235	125
4.0	±.189	-235	125
6.0	±.189	-235	125

Calc 4 zone size = 20.0 m

0.5	±.153	-310	50
1.0	±.177	-270	90
2.0	±.177	-270	90
3.0	±.177	-270	90
4.0	±.177	-270	90
6.0	±.177	-270	90

RWJ

5/9/95 RWT



The displacements of the dyke wall for a given length and dyke pressure is only slightly sensitive to the zone size. Increasing the zone size by a factor of 2 gives the following error

Old	new	Error
2.5	to 5.0	2 %
5.0	to 10.0	3.1 %
10.0	to 20.0	6.5 %

RWT

5/9/95 RWT

The crack growth is sensitive to the zone size. This is because a tensile stress is developed across the dyke some 100 m ahead of the pressured region. The smaller zone size allows ~~the~~ a ~~finer~~ sharper stress gradient to act on the dyke. As the zone size is increased, the stress gradient across the dyke spreads out. Thus the tensile stress reduced at a distance from the pressurized region and a short region of the dyke is broken.

For this purpose the length of the fracture beyond the pressurized region is not a important parameter in that the pressurized region is taken to the fault/dyke intersection. Thus our criteria is that the dyke growth is at least two or more zone lengths to allow the dyke to fracture if possible before the pressurized region reaches the intersection.

The Δt for each zone size is

Zone size (m)	Δt (msec)
~~0.25~~ 2.5	.25
~~0.50~~ 5.0	.501
10.0	.98
20.0	1.78

To do the calculations in a reasonable time we would like at least a 1 msec time step which indicates a 10 m zone size. This results in about a 5% error in displacement and 125 m growth of crack tip which seems to be a reasonable compromise. RWT

5/9/95 RWT

Sensitivity Study on dyke length

Designed possible 12 calculations to define crack growth parameters as a function of initial dyke length.

Set up 1st 4 calc as follows using a zone size ~20m.

Calc #	Crack tip depth (m)	Crack end depth (m)	Crack Length (m)
1	-300	-500	200
2	-300	-700	400
3	-300	-900	600
4	-300	-1100	800

5/10/95 RWT Results

Calc #1 crk length 200 L = 50 m

Contour	F	G	H	I	End
Depth	-250	-290	-320	-380	-500
Disp	.033	.068	.100	.132	.159
Error range	±.003	±.010	±.010	±.014	±.017

Calc #2 crk length 400 L = 50m

Contour	F	G	H	I	End
Depth	-260	-310	-380	-510	-700
Disp	.043	.092	.138	.184	.221
Error range	±.000	±.004	±.007	±.010	±.012

Calc #3 crk length 600 L = 70m

Contour	F	G	H	I	End
Depth	-270	-340	-490	-670	-900
Disp	.062	.124	.185	.247	.298
Error range	±.004	±.011	±.014	±.018	±.022

Calc #4 crk length 800 L = 70 m

Contour	F	G	H	I	End
Depth	-290	-400	-620	-840	-1100
Disp	.080	.161	.241	.322	.386
Error range	±.002	±.003	±.006	±.007	±.009

5/10/95

Set up calculations 5 → 8 on continued study on dike length

Calc #	Crack tip depth (m)	Crack end depth (m)	Crack Length (m)
5	-300	-1300	+1000
6	-300	-1500	+1200
7	-300	-1700	+1400
8	-300	-1900	+1600

5/11/95 Results

Calc #5 crk length 1000 L = 50 m

Contour	F	G	H	I	End
Depth	-310	-500	-750	-960	-1300
Disp	.090	.180	.269	.359	.431
Error Range	±.002	±.004	±.007	±.011	±.012

Calc #6 crk length 1200 L = 50 m

Contour	F	G	H	I	End
Depth	-310	-480	-720	-980	-1500
Disp	.091	.183	.276	.367	.440
Error Range	±.002	±.003	±.004	±.006	±.007

Calc #7 crk length 1400 L = 50m

Contour	F	G	H	I	End
Depth	-310	-500	-750	-1000	-1700
Disp	.095	.198	.285	.380	.460
Error Range	±.003	±.002	±.011	±.012	±.011

Calc #8 crk length 1600 L = 70 m

Contour	F	G	H	I	End
Depth	-310	-520	-780	-1040	-1900
Disp	.098	.195	.294	.391	.470
Error Range	±.001	±.003	±.004	±.006	±.007

5/11/95 RWT

Set up 4 calculations on crack length

Calc #	Crack Tip Depth (m)	Crack End Depth (m)	Crack Length (m)
9	-300	-2100	1800
10	-300	-2300	2000
11	-300	-2500	2200
12	-300	-2700	2400

Noticed some occilation of dyke wall. Suppect zone size discontinuity and nearness of boundaries. Moved Teed boundary from ±100 to ±200. Moved XMIN & XMAX boundary from ±500 to ±1000.

5/12/95 RWT

Learning Opertunity - displacement for calculations at 1000m width are twice the displacement for XMAX = 500. Need to reconsider the impact of boundaries in XMAX and XMIN direction when using ~~the com~~ Uniaxial compression curve. Occilations were not corrected - Will continue crack length series over weekend while retheinking boundary problem -

Reset up problems 9 thru 12 with XMAX = -XMIN = 500 m -

5/15/95 RWT

Results of Calc 9 thru 12

Calc #9 crk length 1800m L = 70m

Contour	F	G	H	I	End
Depth	-310	-520	-770	-1050	-2100
Disp	.097	.193	.289	.385	.460
Error Range	±.004	±.008	±.012	±.015	±.015

Calc #10 crk length 2000m L = 70m

Contour	F	G	H	I	End
Depth	-310	-520	-770	-1040	-2300
Disp	.097	.195	.293	.390	.468
Error Range	±.002	±.003	±.004	±.006	±.007

Calc #11 crk length 2200m L = 70m

Contour	F	G	H	I	End
Depth	-310	-540	-790	-1040	-2500
Disp	.100	.201	.301	.400	-.480
Error Range	±.003	±.005	±.008	±.012	±.014

Calc #12 crk length 2400m L = 70m

Contour	F	G	H	I	End
Depth	-310	-500	-760	-1020	-2700
Disp	.098	.196	.294	.392	.470
Error Range	±.001	±.001	±.002	±.004	±.004

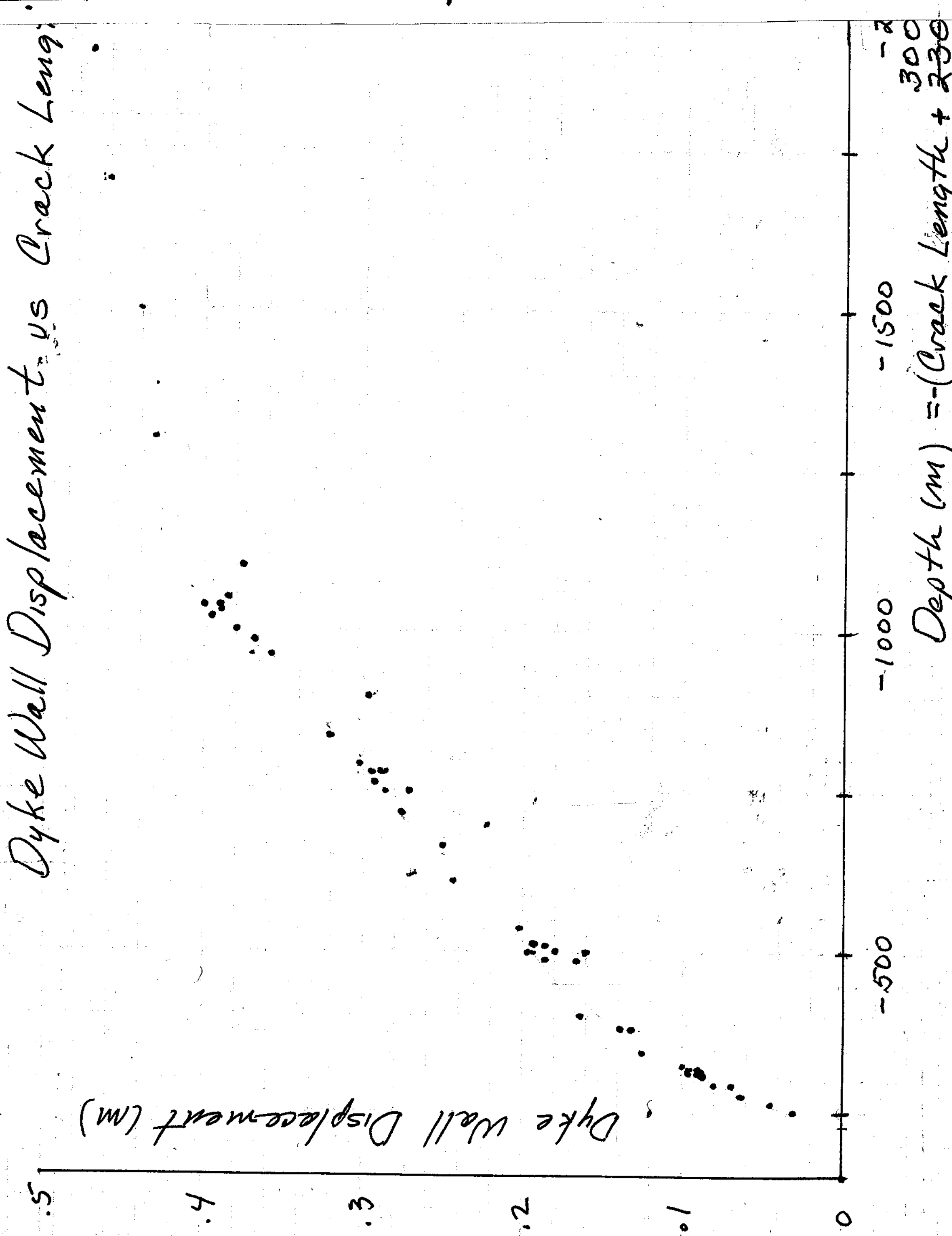
SEE Plot of Calc # 1-12 page 38

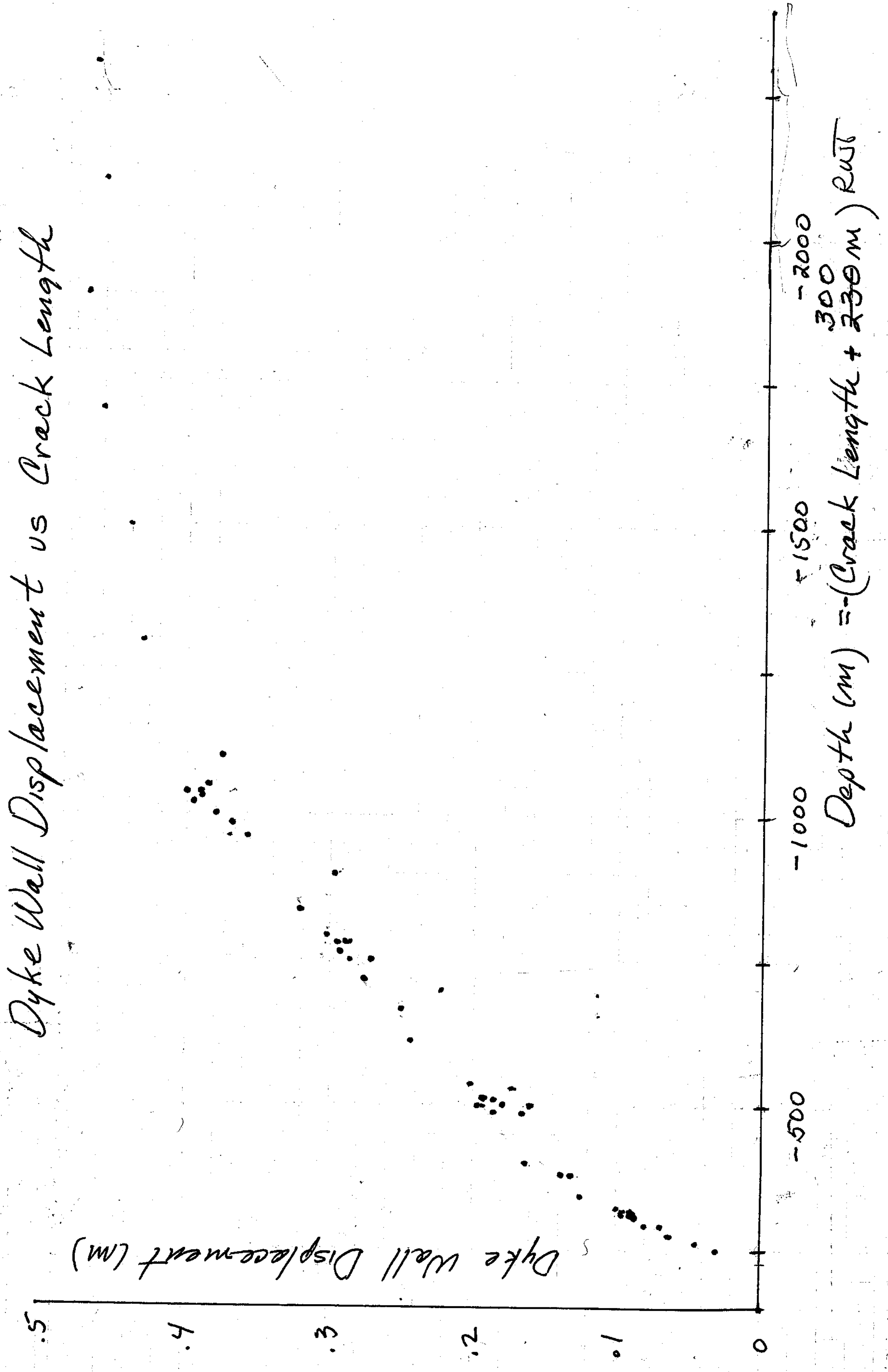
Set up calculation to examine Grid width

Calc #1 XMIN/XMAX = -1000/+1000
Hydrostatic EOS

Calc #2 XMIN/XMAX = -1500/+1500
Hydrostatic EOS

5/15/95 RWT


Dyke Wall Displacement vs Crack Leng
Depth (m) = -(Crack Length + 300)
Dyke Wall Displacement (m)
-500
-1000
-1500
0
.1
.2
.3
.4
.5



5/15/95 RWT
It seem clear from plot on page 38 that the same crack shape is calculated independent of the length of the dyke modeled. Thus once it is known what the maximum width is for a given EOS, dyke pressure and boundary location then a shorter dyke crack can be used for the ~~ca~~ calculations of the fault/dyke interaction.

5/16/95 Grid width Calc -
Calc #1 EOS = hydrostatic XMAX = 1000m pr = .03
Max disp = 0.533 disp@ 900m = .0625
Crk complete to surface ~ disp ~ 0.18
Calc #2 EOS = hydrostatic XMAX = 1500m pr = .03
Max disp = 0.567 disp@ 1400m = .0625
Crk complete to surface disp ~ 0.2

While the max displacement is approximately the same for each calculation, the opening of the dyke to the surface is unacceptable for the purposes of this study. The displacement near the boundary is about the same for both calculations showing that the boundary of zero strain is beyond the current boundaries - Use uniaxial EOS

Since the study is comparing one calculation with another, the overall effect of the boundary is not as important as the boundary effect is the same for all calculations. Ideally the boundary effect should be reduced to zero but this may not be practical in that the grid may be too large for the analyses to be done in a reasonable time. In fact it is not clear that a zero effect is attainable.

All the previous sensitivity studies were done with a pr = .03 and the boundary at XMIN = -500m and XMAX = +500m.

5/15/95
We intend to stay with this general configuration but will now conduct a sensitivity study on the relationship between "pr" the dyke pressure, the boundary location and the dyke wall displacement and crack tip growth –
Based on the previous calc on dyke length for pdr=0.03 GPa the horizontal width of 500 m gave a displacement of ~0.5 and 1000 m gave a displacement of ~1.1, we estimate that a pdr=0.02 GPa @ 1000 m width and pdr=0.015 GPa @ 1500 m width will give a displacement of 0.5 m

Calc Width ~~07~~ 03
pdr=0.02 GPa XMAX=+1000
EOS=Uni YMIN=-1700
Calc Width 04
pdr=0.015 GPa XMAX=1500
EOS=Uni YMIN=-1700
Calc Width 05
pdr=0.015 GPa XMAX=1000
EOS=Uni YMIN=-1700
Calc Width 06
pdr=0.01 GPa XMAX=1500
EOS=Uni YMIN=-1700
5/17/95
Removed Width 03 @ t=1.5 sec as displacement near 0.7 m.

Width 04 Results for XMAX=1500

time	Disp	L
2.0	.755	290
2.5	.895	290
3.0	.618	290

RWT ~~to~~ 5/17/95 RWT

Width 05 results for XMAX=1000

t	Disp	L
1.5	.500	70
2.0	.533	110
2.5	.488	110
3.0	.579	110

Width 06 : results for XMAX=1500

t	Disp	L
1.5	.402	90
2.0	.509	90
2.5	.576	150
3.0	.429	190

The occilations seemed to be enhanced when the boundraries are extended out. Thus the occilations may be due to the length of the dyke crack. I noticed that the short dyke length used for the zone sensitivity studies did not occillate at all.
Increasing the boundary to 1000 m requires the dyke pressure be reduced to less than 0.015 GPa.
Increasing the boundary to 1500 m requires the dyke pressure be reduced to less than 0.010 GPa.
This agrees with the paper by Lester where the overburden stress is not important in the dyke displacement and the tensile strength of the dyke is not important.

5/17/95 RWT
Setup four problem to determine the sensitivity of the calculations to the magma velocity.

Calc#	Vel m/s	Zone size	tip depth	pr GPa	YMAX m	XMAX m	Δt(s)
01	–	20	-500	0.03	-1000	-500	4
02	5.	20	-500	0.03	-1000	-500	26
03	10	20	-500	0.03	-1000	-500	13
04	20	20	-500	0.03	-1000	-500	9

Calc Vel01 determines crack width and tip growth for a open crack.

Calc Vel02 Starts a pressure pulse at a depth of -500m toward the surface at time 1.5 s peaking at 2.0 s. The velocity of the pulse is 5 m/s

Calc Vel03 and Vel04 are the same as Vel02 except the pulse velocity is 10 m/s and 20 m/s respectively

5/19/95 RWT
Calc Vel01 finished @ 6.0 sec Velocity 0 m/s. Pressurized dyke from -500 m to -1000 m. Zoning is 20 m, YMIN = -1000 m YMAX = 0.0 XMIN = -500. XMAX = +500.
EOS was Uniaxial compression and case 1 strength.

5/19/95
Results of Vel01 - stationary dyke pressure

Time (s)	Disp. (m)	Tip Depth (m)	Time (s)	Disp. m	Tip Depth (m)
0.5	.273	-450	3.5	.339	-430
1.0	.307	-450	4.0	.331	-430
1.5	.339	-430	4.5	.328	-430
2.0	.337	-430	5.0	.342	-430
2.5	.322	-430	5.5	.328	-430
3.0	.336	-430	6.0	.328	-430

The displacement of ~0.33 agrees with the plot on page 38 if we add ~250 to the crack ~~depth~~ length of 500 m and check the depth for 750 m.

5/22/95
Calc Vel04 and calc Vel03 completed–
Visit by Larry McKaque of ~~IPT~~ SRI to IPT
Discussed notebook and some calculational results
Set up Vertical fault calculation Dip90a

Dip90a same as Vel04 except tensile strength of dyke bond changed from 0.03 GPa to 0.0 GPa between depths of -200 m and -300 m.
Vel04 and Dip90a had a constant dyke pressure between depths of -500 m to -1000 m and a pressure front propagating upward from -500 m depth at a velocity of 20 m/s.

5/23/95 RWT

Results from Calc Vel04   Vel = 20 m/s

Time (s)	Disp	Tip depth	Time	Disp	Tip depth
0.5	.273	-450	9.0	.338	-310
1.0	.307	-450	9.5	.340	-310
1.5	.339	-430	10.0	.333	-290
2.0	.337	-430	10.5		
2.5	.323	-430	11.0	.334	-290
3.0	.336	-430	11.5	.336	-270
3.5	.340	-390	12.0	.332	-250
4.0	.330	-390	13.0	.334	-250
4.5	.333	-390			
5.0 (5.5)	.343	-390			
6.0	.328	-390			
6.5	.334	-370			
7.0	.342	-350			
7.5	.331	-350			
8.0	.332	-330			
8.5	.342	-330			
	.340	-330			

The pressure front started at 1.5 s at -510 m and ramped up to a pressure of 0.03 GPa at 2.0 s, and traveled toward the surface at a velocity of 20 m/s. The crack tip extended to a depth of -430 m from -500 m due to the initial pressurization of the dyke from -500 m to -1000 m. Due to the courseness of the zoning (20 m zones) the dyke crack tip may jump 20 to 40 m at over a time edit of 0.5 s. The dyke crack tip varies in distance ahead of the pressure front less than 80 m and more than 40 m. When the pressure fronts stops at -300 m depth, the crack tip stops at -250 m. The unpressurized crack length is approximately 50 to 70 m —

5/23/95 RWT

Results from Calc Vel03   Vel = 10 m/s

Time (s)	Disp	Tip Depth	Time (s)	Disp	Tip Depth
0.5	.273	-450	10.5	.331	-370
1.0	.307	-450	11.0	.344	-350
1.5	.339	-430	12.0	.332	-350
2.0	.337	-430	13.0	.342	-350
2.5	.322	-430	13.5	.329	-330
3.0	.336	-430	14.0	.349	-330
3.5	.339	-430	14.5	.335	-330
4.0	.332	-430	15.0	.333	-310
4.5	.329	-430	16.0	.343	-310
5.0	.342	-410	17.0	.352	-310
5.5	.330	-410	17.5	.336	-290
6.0	.328	-410	18.0	.332	-290
6.5	.342	-410	19.0	.340	-290
7.0	.335	-410	19.5	.333	-270
7.5	.330	-390	20.0	.346	-270
8.0	.343	-390	21.0	.332	-270
8.5	.340	-390	21.5	.354	-250
9.0	.324	-390	22.0	.338	-250
9.5	.341	-370	23.0	.346	-250
10.0	.338	-370	24.0	.338	-250

The pressure front started at 1.5 s at -510 m and ramped up to a pressure of 0.03 GPa at 2.0 s and traveled toward the surface at a velocity of 10 m/s. Similar to Calc Vel04 the crack tip remaind ahead of the pressure front a distance between 40 and 70 m. When the pressure front stops at a depth -300 m the crack tip is 50 meters above the pressure from which is identical to Calc Vel04. No difference in crack growth except for rate is observed between Calc Vel03 and Calc Vel04.

5/23/95 RWT

Results for Calc Vel 02

Time(s)	Disp	Tip depth	Time(s)	Disp	Tip depth
0.5	.273	-450	21.0	.327	-350
1.0	.307	-450	22.0	.343	-350
1.5	.339	-430	23.0	.352	-350
2.0	.337	-430	24.0	.332	-350
2.5	.332	-430	24.5	.350	-330
3.0	.336	-430	25.0	.346	-330
3.5	.339	-430	25.5	.327	-330
4.0	.332	-430	26.0	.356	-330
4.5	.328	-430	27.0	.337	-330
5.0	.343	-430	28.0	.349	-330
5.5	.329	-430	28.5	.336	-310
6.0	.327	-430	29.0	.354	-310
6.5	.340	-430	30.0	.335	-310
7.0	.337	-430	31.0	.342	-310
7.5	.327	-430	32.0	.335	-310
8.0	.339	-410	32.5	.346	-310
8.5	.342	-410	33.0	.343	-290
9.0	.319	-410	34.0	.345	-290
10.0	.337	-410	34.5	.342	-290
11.0	.344	-410	35.0	.350	-290
12.0	.322	-410	36.0	.334	-290
12.5	.347	-390	36.5	.353	-270
13.0	.340	-390	37.0	.345	-270
14.0	.346	-390	38.0	.354	-270
15.0	.322	-390	39.0	.345	-270
16.0	.343	-390	40.0	.345	-270
16.5	.320	-370	41.0	.351	-270
17.0	.349	-370	42.0	.345	-270
18.0	.327	-370	43.0	.345	-270
19.0	.344	-370	44.0	.351	-270
19.5	.323	-370	45.0	.346	-270
20.0	.352	-350			

5/23/95 RWT

Discussion on Velocity sensitivity study —
The tip of the crack lies in a band some 50 to 70 m ahead of the pressure front independent of the velocity of the front for the velocity range between 5 to 20 m/s. The crack tip propagates with the same velocity as the pressure front. The maximum displacement of the dyke walls is independent of the pressure front velocity.
Next the effect of a flaw in the dyke or a vertical fault in relation to the pressure front velocity will bee studies. See figure page 48

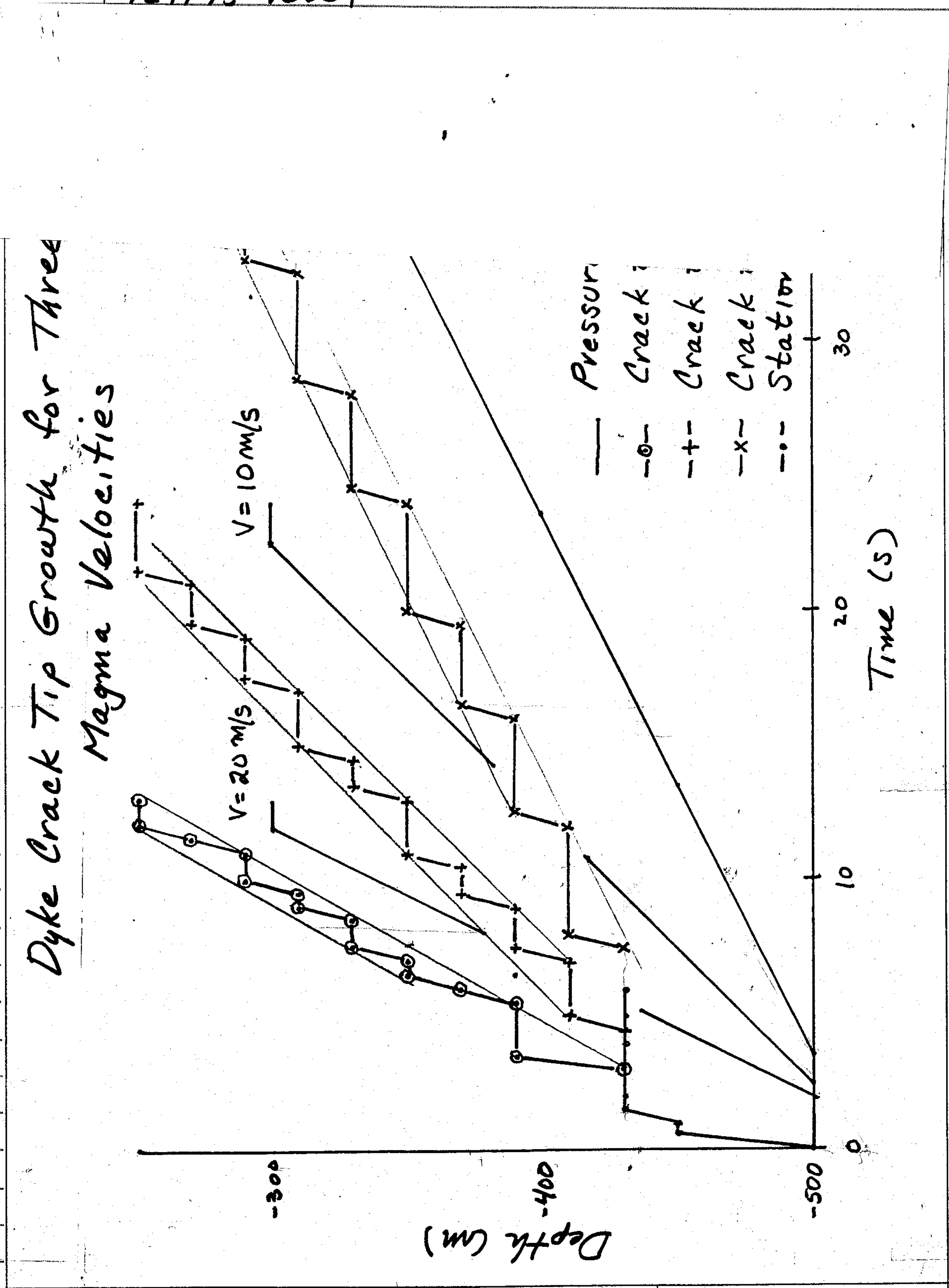
Calc Dip 90a finished @ 20 m/s
Set up Dip 90 b with velocity 10 m/s.

5/24/95 RWT

Results of Dip 90a calculation

Time(s)	Disp. (m)	Tip Depth	Time(s)	Disp.	Tip Depth
0.5	.273	-450	7.0	.328	-300
1.0	.306	-450	7.5	.334	-250
1.5	.339	-430	8.0	.336	-230
2.0	.337	-430	8.5	.333	-230
2.5	.323	-430	9.0	.335	-230
3.0	.336	-430	9.5	.340	-210
3.5	.341	-390	10.0	.333	-210
4.0	.330	-390	10.5	.336	-190
4.5	.333	-390	11.0	.340	-190
5.0	.339	-390	11.5	.334	-190
5.5	.331	-390	12.0	.334	-190
6.0	.334	-350	12.5	.334	-190
6.5	.341	-330	13.0	.334	-190

5/24/95 RWT



5/24/95 RWT

Results of Calc Dip 90b

Time(s)	Disp	Tip Depth	Time(s)	Disp	Tip Depth
0.5	.273	-450	10.0	.337	-330/~~300~~ ~~290~~ -310 RWT
1.0	.306	-450	10.5	.329	-290
1.5	.339	-430	11.0	.343	-250
4.5	.329	-430	11.5	.335	-250
5.0	.340	-410	12.0	.329	-250
7.0	.335	-410	12.5	.347	-250
7.5	.329	-390	13.0	.338	-250
9.0	.334	-390	13.5	.330	-230
9.5	.341	-350/~~300~~ -290 RWT			

Discussion of Dip 90 a & b calculations

The magma pressure was simulated by a pressure against the dyke walls. For the first 1.5 sec the pressure was applied to the dyke wall between the depths -500m to -1000m. The dyke tip grew from -500m to -430m. Then the pressure moved up the dyke surface at a given velocity. The dyke crack tip broke the bonds holding together ~~with~~ the dyke with a tensile strength of 0.036Pa. Because of the course zoning the tip moved in a jerky fashion but staying in a band between 50 to 70m ahead of the magma pressure front. This was true for velocities of the magma of 5m/s, 10m/s and 20m/s.

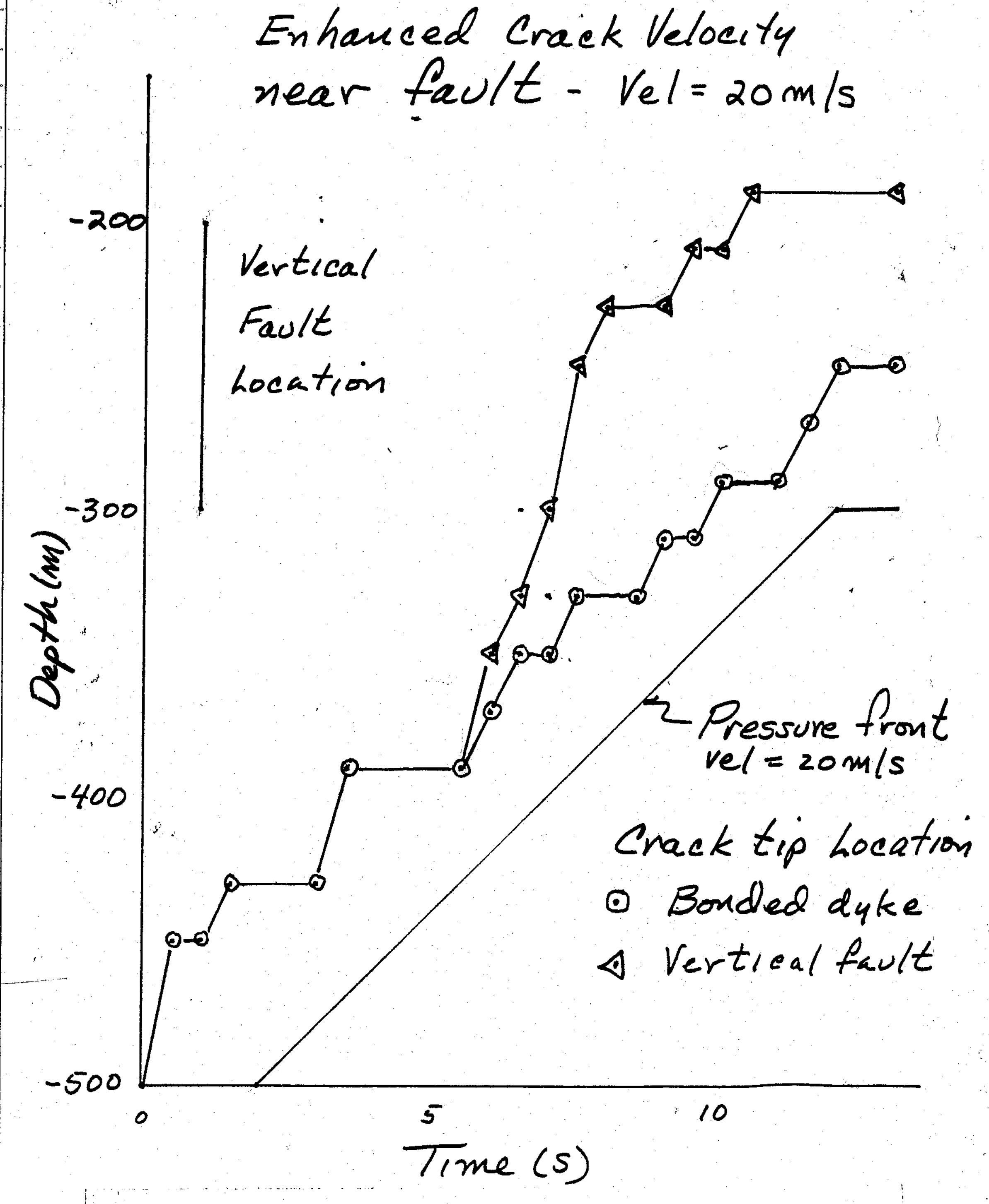
We suspected that a flaw or crack above the dyke might influence the dyke crack tip propagation. Dip90a was identical to Vel04 where the magma velocity was 20m/s, except the tensile strength of the bonds between -300 and -200

5/24/95 RWT
in depth were set to zero. Dip90a calculation results were essentially the same as Vel04 until the crack tip reached a depth of -390 m. At this point the dyke crack tip velocity increased towards the fault (simulated)
Dip90b was the same as Vel03 with a velocity of 10 m/s. A fault was simulated the same as in Dip90a - The results of calculation Dip90b was the same as Vel03 except again when the dyke crack tip reached a depth of -390 m the crack tip accelerated toward the fault. In both cases the fault opened up completely.
I suspect we may see the dyke crack tip accelerate as it nears a fault which means that each calculation may not have to run as long as originally anticipated.
Although each Dip90 calculation showed the tip acceleration when the tip was 90 m from the fault, this may be due in part ~~that~~ to the orientation of the fault and the length of the fault. A open void may behave differently.

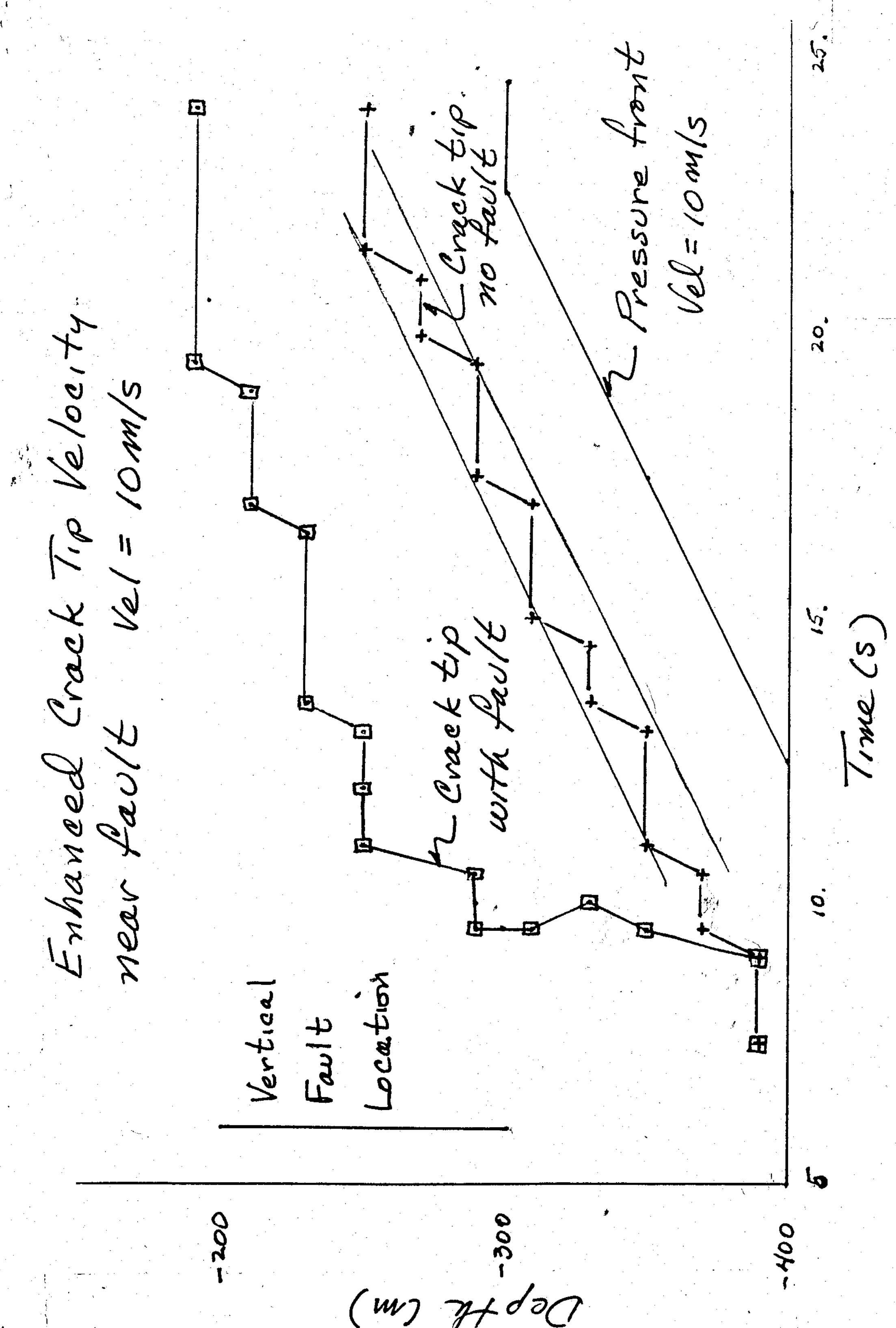
The plots for Dip90a and Vel04 are shown on page 51

The plots for Dip90b and Vel03 are shown on page 52.

5/24/95 RWT



5/24/95 RWT

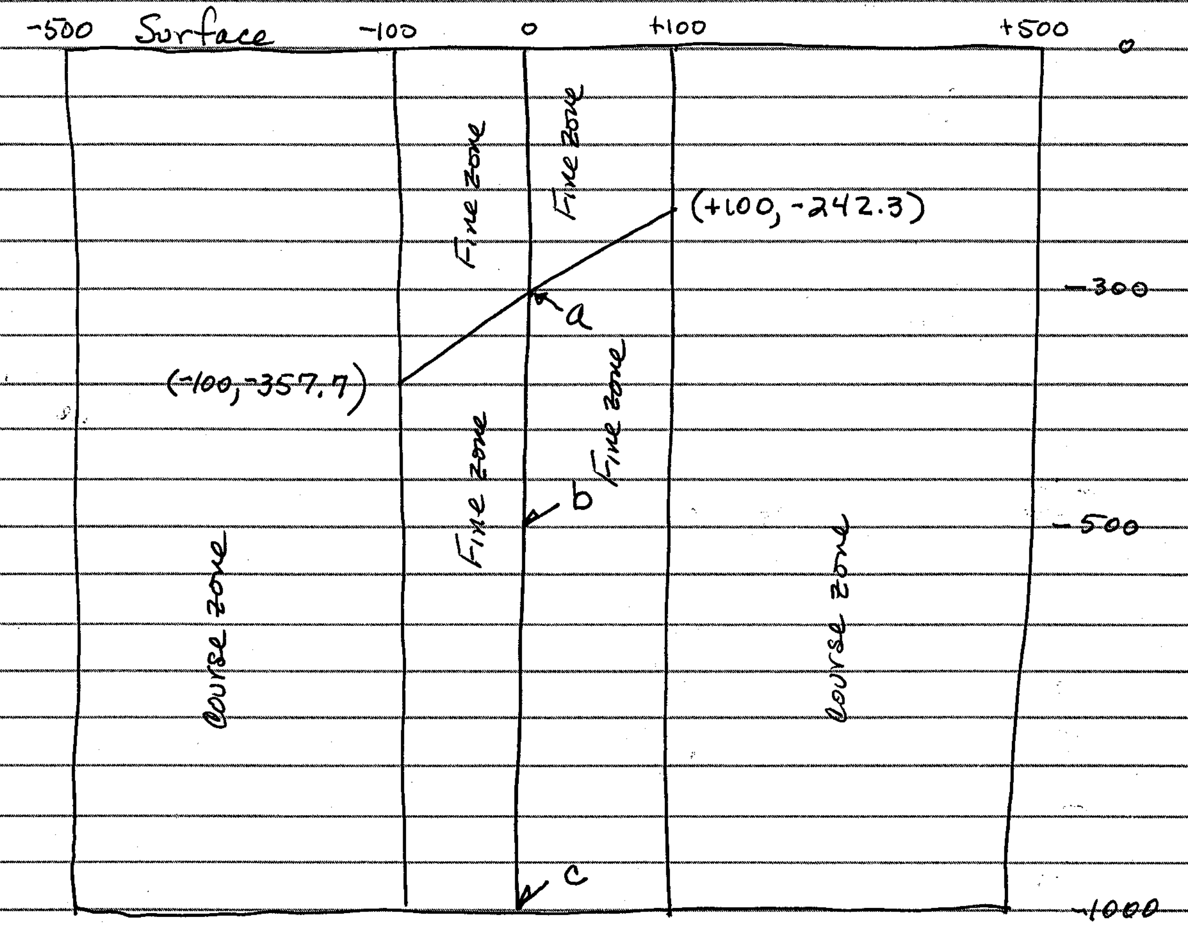


5/25/95 RWT

Continuation of results from Dip 90b

Time	Disp	Tip Depth	Time	Disp	Tip Depth
13.5	.330	-230	17.5	.339	-210
14.0	.348	-230	18.0	.337	-210
14.5	.330	-230	18.5	.342	-210
15.0	.337	-230	19.0	.341	-210
15.5	.343	-230	19.5	.335	-190
16.0	.333	-230	20.0	.347	-190
16.5	.338	-230	20.5	.336	-190
17.0	.340	-210	21.0	.337	-190
			22.0	.333	-190
			23.0	.344	-190
			24.0	.343	-190

Set up Dip30a for long weekend



5/25/95 RWT

Depth300m Dip30a setup

Dip30a

- Fine zone region: 10 m zones next to dyke increasing to 15 m zones at ±100 m
- Coarse zone region: 20 m zones next to fine zone region increasing to 40 m near boundary.
- Equation of state - Uniaxial compression and CASE 1 high strength curve
- Dyke tensile strength 0.03 GPa
- Dyke pressure increases from 0 GPa to 0.03 GPa in 0.5 seconds and remains constant.
- Dyke pressure applied simultanously to dyke region between points "b" to "c".
- Dyke pressure propagates from point "b" to point "a" at velocity of 20 m/s.
- point "a" at depth -300m
- point "b" at depth -500m
- point "c" at depth -1000m

5/26/95

Dip30a still running @ 2.7 sec

5/30/95 RWT

Depth300m Dip30a complete - Results

Dip30a

Time (sec)	Disp (m)	Crk Tip Depth (m)	Time (sec)	Disp (m)	Crk Tip Depth (m)
0.0	0.0	-500	6.5	0.353	-315
0.5	0.280	-415	7.0	0.350	-315
1.0	0.325	-415	7.5	0.365	-315
1.5	0.350	-405	8.0	0.353	-300
2.0	0.350	-405	8.5	0.353	-300
2.5	0.336	-395	9.0	0.360	-300
3.0	0.362	-385	9.5	0.357	-300
3.5	0.350	-375	10.0	0.353	-300
4.0	0.345	-365	11.0	0.356	-300
4.5	0.365	-355	12.0	0.365	-300
5.0	0.355	-355	13.0	0.361	-300
5.5	0.342	-345	14.0	0.365	-300
6.0	0.366	-335			

Ran stress contours and noticed early tension contours at ends of fault (-100, -357.7) and (+100, -242.3). Fault opened up and tried to extend at upper end toward surface. Suspect that the artifical termination of the fault influenced the results.

Depth300 Dip30b Set up a new problem Dip30b where the finezone region was extended to horizontal distances of ± 250 m. 12.5* Increased zone size from 10 m to 15 m size zones. Increased magma velocity to 40 m/s to speed up calculation.

5/31/95 RWT
Dip 30 b still running – Prob @ 3.0 sec
noticed a bond failure above fault at
433 msec. (At -300 m depth).
Stress contour showed only compressive
stresses along fault and near points
where fault terminate.

~~5/3~~ 6/1/95
Depth 300 m Dip 30 b – complete – after 2.5 sec
Dip 30b bonds broke in erratic manner. Data
below –

Node #		Depth		Time step
z=0	z=-20	-600		+
431	432	-585		104
429	430	-570		211
427	428	-555		228
425	426	-540		245
423	424	.		261
421	422	-525		278
2311	2312	-300	Above fault	287
419	420	-510		332
417	418	-495		383
415	416	-480		875
413	414	-465		884
411	412	-450		1484
	410	-435		1492
407		-420		2089
	406	-405		2105
403		-390		2591
	402	-375		2716
399		-360		3178
	398	-345		3237
395		-330		3699
	394	-315		3819
391		-300		3826

6/1/95 RWT
Dike did not propagate past ~~dyk~~ fault
and fault did not open or move. Suspect
that use of high magma velocity may have
been a error. The dyke pressure is
insufficient to open up the dyke by itself
but requires the leverage of the crack
tip. The tensile strength is the same as
the dyke pressure ~ 0.030 GPa – Some
of the bonds did not break – nodes at
409, 408, 405, 404, 401, 400, 397, 396, 393, 392

Summary – Extension of ~~dike~~ fault to ±250 m
appears to work to elliminate tension
focusing on the ends of the fault.
Increasing the magma velocity to 40 m/s
may have exceeded a limit for modeling
the dyke magma pressure in that a low
stress can get far up the dyke before the
max stress can open up the dyke crack.
Need to test a magma velocity of 40 m/s –

Set up Vel05 – like Vel04 except
for following –
1. Extended fine zone region from
∓100 to ±250 m
2. Reduced zone size from 20 m
to 15 m in fine zone region
3. Increased velocity of magma from
20 m/s to 40 m/s

6/2/95 RWT
Results for Vel 05 – many bonds
did not break but these were closer to
intersection than Dip30 b.

6/2/95 RWT

Data for Vel05 is as follows.

Depth	Bond at 0	Bond at -20	Time
-330	yes	yes	5.4
-300	yes	NO X	5.84
-315	X NO	yes	5.85
-280	X No	yes	7.08
-260	yes	NO X	7.65

The greater number of bonds not breaking on cable Dip30b could be due to some strain relief caused by the fault or possibility due to some unknown reason associated with widening the fine zone region. It appears that the velocity is a factor but may not be the only factor causing the not breaking of the bonds in the pressurized region.

Created Vel06 the same as Vel05 except the magma velocity is 20m/s.

Created Pres01 for dyke calculation at depth of 2000 m. Pres01 same as Vel05 except grid extend from surface to -2700 meters. Purpose of Pres01 is to check if the magma pressure of 0.03 GPa gives a wall displacement of 0.33 to 0.35 m as the calculations for a depth of 300 m did.

6/5/95 RWT

Data for Vel06 as follows

Depth	Bond at 0	Bond at -20	Time
-330	Y	Y	9.8
-315	Y	Y	11.8
-280	(N)	Y	12.2
-300	Y	(N)	13.6
-260	Y	(N)	15.1
-240	(N)	Y	15.2

Vel06 had same problem as Vel05 so its not the velocity of the magma — !!!

Recap –

Dip30b	Vel = 40 15m Vert change in zone size @ -300 fine zone to 250 m	Assymetric zones
Vel05	Vel = 40 15m Vert change in zone size @ -300 fine zone to 250 m	←
Vel06	Vel = 20 15m Vert change in zone size @ -300 fine zone to 250	←

IN Dip30b – erratic breaking of bonds over most of dyke

IN Vel05 – erratic breaking near -300 m

IN Vel06 – erratic breaking near -300 m

Pres01 results —

Crack tip grew from -2150 m to -1950 m due to opening of pressurized region from -2150 to -2700 m. Although Pres01 had same zoning as Vel05 there was no erratic breaking of the bonds at -2000 m.

6/5/95 RWT

Data for Pres01 as follows

Time (s)	Crack Tip depth (m)
.14	-2150
.236	-2135
.248	-2120
.270	-2105
.282	-2090
.316	-2075
.328	-2060
.366	-2045
.380	-2030
.424	-2015
.434	-2000
2.092	-1980
2.108	-1960

Time	Wall Disp (m)
0.5	.349
1.0	.381
1.5	.391
2.0	.397
2.5	.405

The crack tip is 200 ahead of the pressure front for the calc at 2. km while the crack tip is 70 ahead of the pressure front for the calc at 300 m. The crack shape however is about the same for both 2. km & 300m.

Take 2700 - 2150 = 550 crack length original which should give from figure on page 38 a displacement of 0.33 (550+300) = 850 The crack however is 200 m longer at 0.5 S which gives (1050 depth) and crack width of 0.39 to 0.4 as observed in calc.

See page 62 6/6/95 RWT

Two problems

1. Why the longer crack length with depth?
2. Why no erratic breaking of bonds. like Vel05?

6/5/95 RWT

Setup Len01 (Len2km01) same as ~~pressure~~ Pres01 except as follows. Changed zoning to be constant between -1700 m and -2300 m. Changed fine zone boundary to ± 240 m. Extended grid to depth of -4800 m. Refined zoning to surface. magma pressure = 0.03 GPa between -2300 to -4800. Set stop time to 4. sec for static problem - ie (no magma velocity pulse)

Setup Vel07 same as Vel06 except changed zoning from surface to -500 to be constant 20 m. Change fine zone region boundary to ± 240 m. Magma pressure 0.030 Magma velocity 20 m/s, starting at -500 m to -300 m. Constant pressure from -500 m to -1000 m.

6/6/95

Len2km01 results

Time	Disp	Crk Tip
0	0	-2300
0.5	.332	-2170
1.0	.365	-2170
1.5	.356	-2170
2.0	.357	-2170
2.5	.361	-2170
3.0	.372	-2170
3.5	.366	-2130
4.0	.380	-2130

The maximum displacement is not at -4800 but at -2900 m. At -4800 the ~~max~~ wall disp is approx 0.25 m. The increase in the crack tip growth at 3.5 & 4.0 sec is due to the

6/6/95 RWT

response of the overburden trying to close the crack at depths below -4000m

Depth	Disp Time = 1.05	Time = 4.05
-2130	0	0
-2170	0	.08
-2300	.15	.16
-2400	.22	.24
-2500	.30	.32
-2900	.365	.380
-3300	.300	.310
-3500	.295	.280
-3600	.295	.280
-3700	.290	.290
-4000	.290	.310
-4200	.280	.280
-4800	.250	.220

Solution to Problems
Vel 07 showed no sign of erratic bond breaking. The ~~cooks~~ zones remain elastic !!! - maintaining a high tensile stress. ...
The bond tensile strength is 0.030 GPa
The dyke pressure is 0.030 GPa
The rock tensile strength is 0.031 GPa

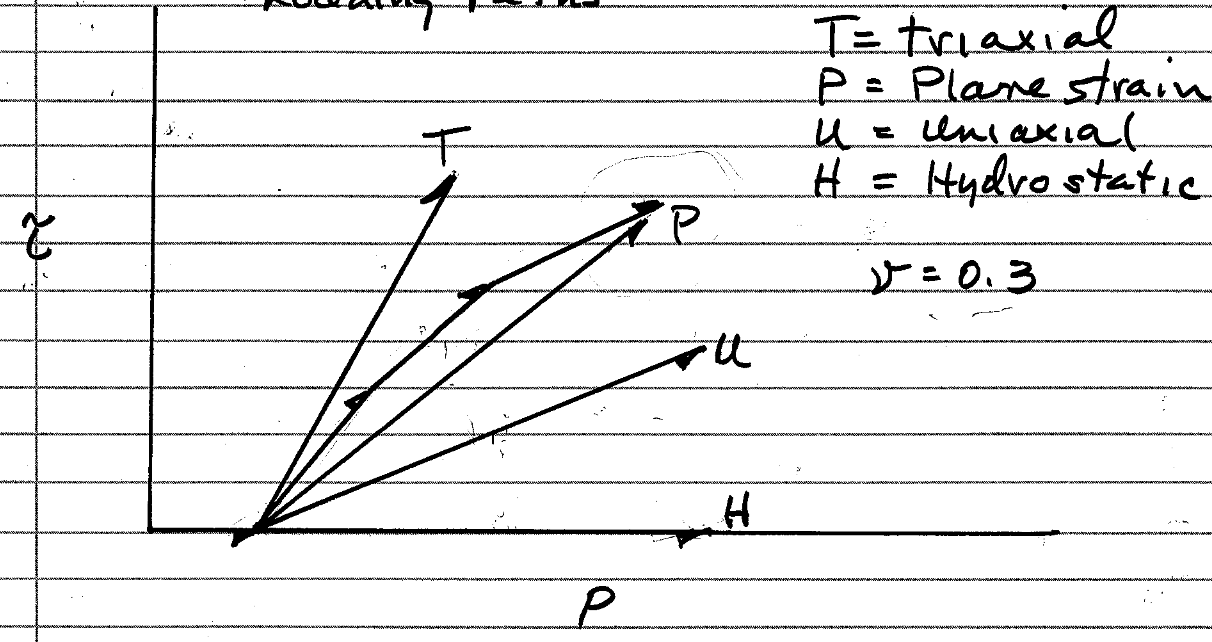
When the zones are symetric around the dyke or the zone are the same ~~size~~ width and length going up the dyke then the bonds break before the tensile strength of the rock in the zone reaches failure. When there is assymeteries or a variation in zone size then the zones can fail befor the neighbor bond fails resulting in erratic bond breaking -

6/6/95 RWT

Because the fault problems are assymetric we need to increase the difference between the bond strength and the tensile strength of the rock such that the bonds fail before the neighboring zones fail.
To increase the ~~zone~~ tensile strength requires considerable effort in developing a new strength curve. The easiest approach is to reduce the bond tensile strength.
With a increase in depth the overborden (Pres 0) pressure moves the zone away from the tensile region. Thus there was no erratic breaking of the bondes even though the zoning was the ~~the~~ same as Vel 05

Longer crack length with depth -
The loading path of the pressure on the dyke wall is plane strain. This loading path is half way between the loading path for ~~hydrostatic~~ triaxial and uniaxial

Loading Paths



6/6/95 RMT
The model first loads the grid as hydrostatic where $\sigma_1 = \sigma_2 = \sigma_3$.
When we use the uniaxial compression for the hydrostatic loading we get at a depth of ~2000 m a 1% compression at .06 GPa in comparison to the 0.3% compression for the hydrostate. Thus the material is much stiffer at depth than at near the surface. In other words using the uniaxial strain compression curve gives a unrealistic effect due to depth. This is something I should have considered initially. The uniaxial compression curve was chosen in a effort to keep the length to the crack tip short to reduce the calculation time. The 2 km depth calc indicate this ~~wou~~ will not happen and defeats the goal of keeping all the calculation the same with the exception of depth and dip angle.

New Plan

1. Recalibrate for hydrostatic eos
2. Recalibrate for new bond tensile strength

Setup Len3m01 same as Vel07 except
YMAX = 0 YMIN = -3000,
compressibility = hydrostatic
dyke pressure = 0.05 bond = .030
4 sec static ie (no magma velocity),

6/7/95 RMT
Results of Len3M01 $T_o = .036Pa$

Time	Disp	Depth	Crk Tip Depth
0	-	-	-500
.5	.356	-900	-370
1.0	.457	-2140	-330
1.5	.435	-1500	-290
2.0	.398	-2700	-290
2.5	.417	-900	-290
3.0	.418	-2100	-290
3.5	.442	-2900	-290
4.0	.448	-2500	-290

Time	Contours / depth F	G	H	I
2.5	.0867/-380	.173/-470	.260/-510	.347/-600
3.0	.0869/-360	.174/-460	.261/-510	.348/-600
3.5	.0917/-400	.184/-480	~~.368~~ .276/-530	.368/-640
4.0	.0936/-380	.187/-470	.280/-520	.373/-620

Maintained bond tensile strength of 0.036Pa to compare with calculations with lower tensile strengths. Problem was symetric so no problem with erratic breaking.

Contour	Avg Disp	Avg Depth
F	.090	-380
G	.180	-470
H	.269	-520
I	.359	-615

Set up Len3M02 same as Len3M01 except bond strength $T_o = .02$ GPa & changed initial crack depth to -600 to allow for increase in crk length with decrease in bond strength

6/8/95 RWT

Results of Len3M02 $T_o = 0.02$ GPa

Time	Disp	Depth	Crk Tip Depth
0	-	-	-600
0.5			
1.0	.466	-2700	-370
1.5	.431	-2100	-370
2.0	.406	-2900	-370
2.5	.410	-900	-330
3.0	.424	-2700	-330

Time	Contour / Depth F	G	H	I
1.0	.096/-500	.194/-590	.290/-650	.387/-750
1.5	.089/-450	.179/-560	.269/-620	.359/-720
2.0	.084/-500	.169/-560	.253/-620	.338/-780
2.5	.085/-470	.171/-560	.256/-610	.341/-690
3.0	.083/-450	.176/-560	.265/-620	.353/-740

Contour	Avg Disp	Avg Depth
F	.087	-470
G	.178	-560
H	.267	-620
I	.356	-740

Set up Len3M03 same as Len3M02 except $T_o = 0.026$ GPa

Set up Len2km02 same as Len3M02 ~~expt~~ except ~~ad~~ subtracted 1700 from all depths & $T_o = 0.020$ GPa

6/9/95 RWT

Results of Len3M03 $T_o = .026$ GPa

Time	Disp	Crk Tip Depth	Contours .0625	.125	.188	.250	.312	.375	.438
1.0		0 - 600							
1.5									
2.0	-.407	-370	-470	-560	-600	-640	-720	-970	
2.5									
3.0	.427	-370	-420	-500	-570	-610	-670		
3.5									
4.0	.447	-330	-400	-500	-560	-600	-660	-780	-1400
	AVG Depth		-430	-520	-580	-620	-680	870	-1400

Results of Len2km02 $T_o = .020$ GPa

Time	Disp	Crk Tip Depth
0		-2300
0.5	.339	-2150
1.0	.425	-2110
1.5	.425	-2010
2.0	.445	-2010
2.5	.412	-2010
3.0		

Time	Contour / Depth F	G	H	I
0.5	.070/-2220	.141/-2290	.211/-2340	.282/-2460
1.0	.083/-2210	.177/-2290	.265/-2320	.354/-2440
1.5	.089/-2160	.177/-2270	.266/-2320	.354/-2440
2.0	.092/-2190	.185/-2280	.277/-2320	.370/-2480
2.5	.086/-2160	.172/-2270	.257/-2320	.343/-2420

6/9/95 RWT

Len2KM02 - Averages -

Contour	Avg Disp	Avg Depth
F	.088	-2180
G	.178	-2280
H	.266	-2320
I	.355	-2450

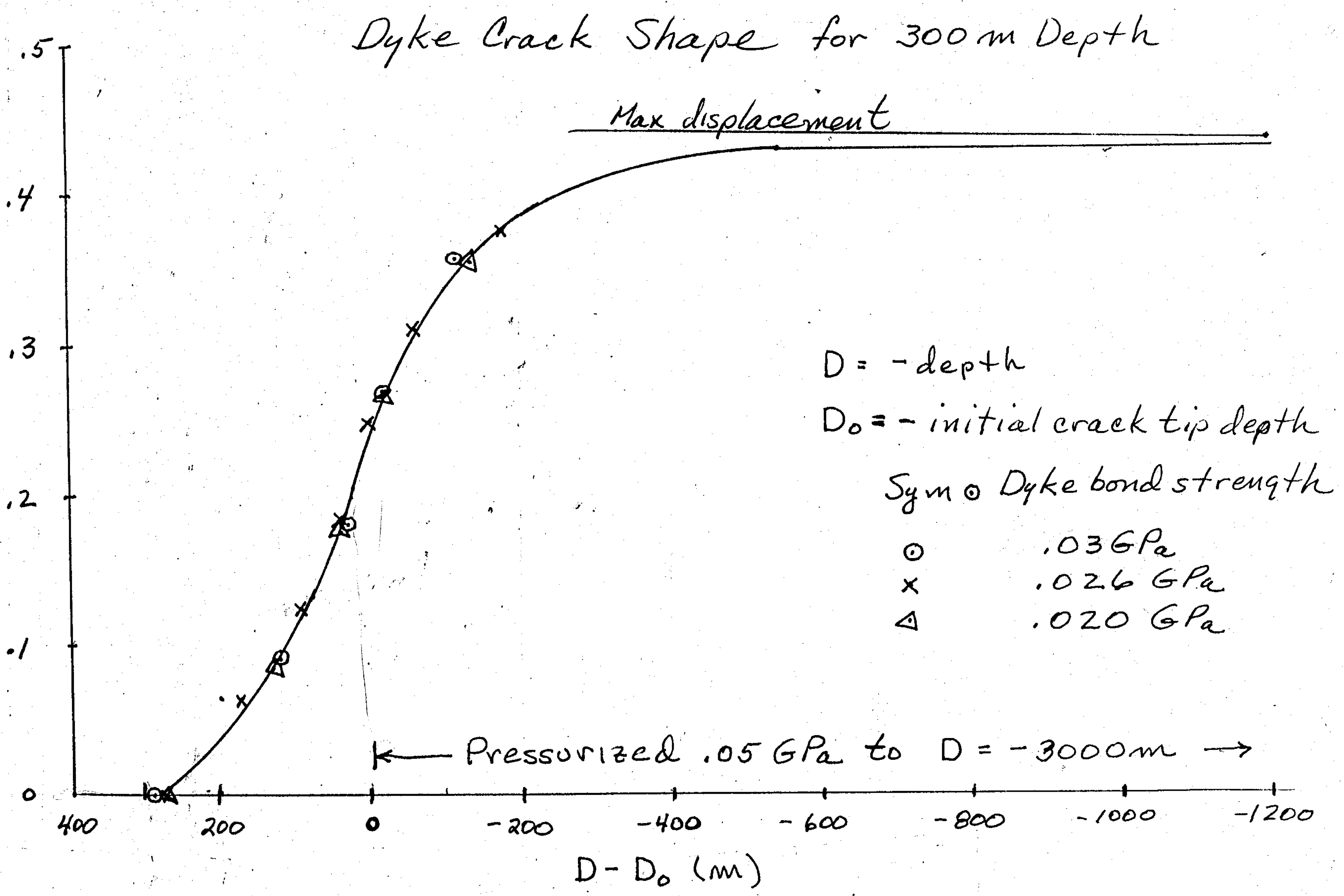
Set up 2 course zoned problems with fault dip of 30°

Depth 300m
Dip30C D300m dip 30° T_0 = .026 GPa
ymin = -1000 ymax = 0.
dyke/fault intersection @ -300m
zone size = 20m
elements = 1656
machine time/element = 9.468 msec
time step = 2.0 msec
1 hr clock time ≈ .480 msec simulated
tip depth = -640m
dyke pressure = 0.05 GPa Vel 20m/s
Compression = hydrostatic
Strength = CASE 1

Depth 2KM
Dip30a D2km dip 30° T_0 = .026 GPA
same as D300m dip 30° except
-1700 added to all depths & zoned to surface
zone size 20m
elements = 2156
machine time/element = 9.721 msec
time step = 2.0 msec
1 hr clock time = 360 msec
Tip depth = -2340 m
dyke pressure = 0.05 GPa Vel 20m/s

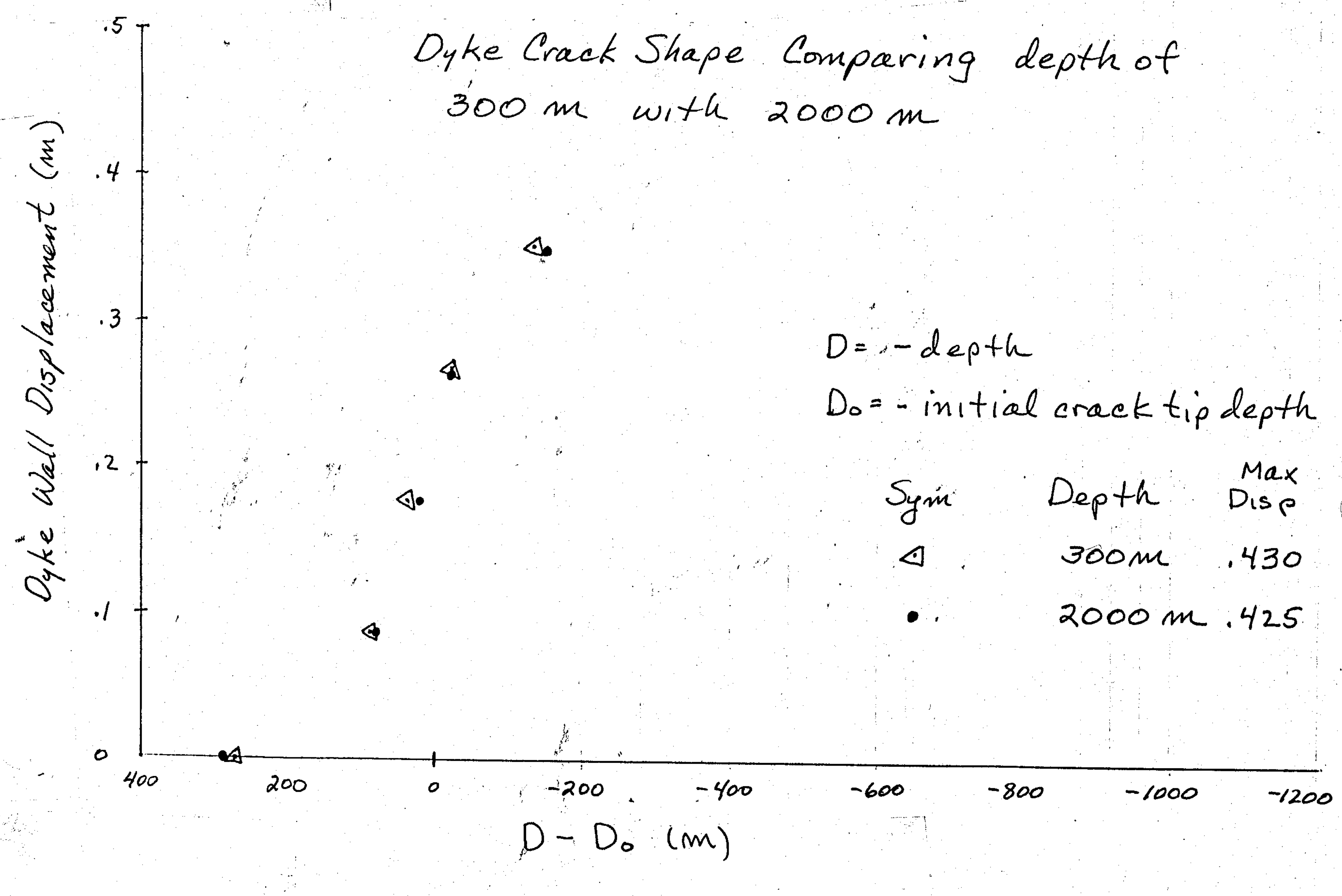
6/12/95 RWT

Below is a plot of dyke crack shape with depth. Negitive values of D-Do are the pressurized region of the dyke & positive values of D-Do are unpressurized crack extention - the results are essentially the same for tensile bond strength of .03 GPa to 0.020 GPa.



6/12/95 RWT

Below is a comparison of the dyke crack shape for depths of 300 m and 2000 m. The crack tip region is apparently independent of tensile strength and depth. At great depths the crack tends to close and vary with depth but at the crack tip the shape is the same. A pressure of 0.05 GPa seems



6/12/95 RevT.
about right to expand the dyke walls to approximately +0.5m.

Depth 300m Dip30C
Results of D300m Dip30° To = .0266 Pa
Problem ran to ~~12 sec~~. 14 sec
Dyke propagated to fault & stopped. Fault displaced ~10 cm but did not open. One bond above ~~dept~~ fault broke but only one. The node bonds across the dyke broke as follows

Node	Depth	Time step	Time
291,92	-640	57	.114
289,90	-620	99	.198
287,88	-600	107	.214
285,86	-580	117	.234
283,84	-560	126	.252
281,82	-540	142	.284
279,80	-520	152	.304
277,78	-500	170	.340
275,276	-480	180	.360
1601,1602	-300*	281	.562
273,274	-460	311	.622
271,272	-440	336	.772
269,70	-420	1193	2.386
267,68	-400	2038	4.076
265,66	-380	2054	4.108
263,64	-360	3937	6.974
261,62	-340	4464	8.928
257,58	-300	5109	10.218
259,60	-320	5963	11.926

* Node on top side of fault.

Depth 2km
Dip 30a

6/12/95 RWT

Results of D2km Dip 30° T_0 = .026
Problem taken off at T = 11.2 sec
dyke did not go past fault.
Results were very similar to the 300m calc –

Node	Depth	TimeStep	Time
291, 92	-2340	59	.118
289, 90	-2320	101	.202
287, 88	-2300	109	.218
285, 86	-2280	126	.252
283, 84	-2260	141	.282
281, 82	-2240	158	.316
279, 80	-2220	174	.348
277, 78	-2200	283	.566
1602, 1601	-2000*	284	.568
275, 76	-2180	308	.616
273, 74	-2160	486	.972
271, 72	-2140	512	1.024
269, 70	-2120	1823	3.646
267, 68	-2100	2753	5.506
265, 66	-2080	3489	6.978
263, 64	-2060	3501	7.002
261, 62	-2040	4473	8.946
257, 58	-2000	4952	9.904
259, 60	-2020	4964	9.928

* On dyke above fault –

The fault did not open but allowed small displacement along the bottom of the fault.

For the parameters we have chosen the dyke will not propagate across a fault of dip 30° or more for depths less than 2 km.

6/12/95 RWT

Question: Will any dyke cross a fault of any dip, depth and assumed tensile strength.

Looked up some typical tensile strengths for some rock types –

Rock Type.	Tensile strength GPa
Granite	.004 < T_0 < .020
Sandstone	.002 < T_0 < .004
Limestone	.004 < T_0 < .008
Marble	.006 < T_0 < .007

The dyke bond strength we have been using is much greater than the range for the typical rocks –

The previous study had a 30° dip fault, T_0 = .031 at 10 km depth where the dyke did propagate through the fault so apparently if the pressure is large enough the fault will lockup and the dyke can propagate across.

Question? – In order to propagate a dyke past a fault.

1. How important is the tensile strength
2. How important the depth
3. How do the above vary with dip?

New parameter study starting with a horizontal fault, a tensile strength of T_0 and vary the depth, then tensile strength, then dip –

dikeparm
parmset4

6/12/95 RWT

Setup D300m Dip 00a To = 0.01 GPa
Horizontal fault intersecting dyke at -300 depth. Set To = .01 GPa dyke pressure = 0.05 ... everything else the same as D300m Dip 30.

6/13/95 RWT

dikeparm
parmset4

Results of D300 Dip00a To = 0.01 GPa
Tip @ -640 Stop time 8.6 sec

Node	Depth	Time Step	Time
1959,60	-640	26	.067
1957,58	-620	46	.119
1955,56	-600	51	.132
1953,54	-580	57	.147
1951,52	-560	62	.160
1949,50	-540	67	.173
1947,48	-520	72	.186
1945,46	-~~480~~500	77	.199
1943,44	-~~300~~480	82	.212
1925,26	-300+	86	.222
1941,42	-460	87	.225
1939,40	-440	92	.238
1937,38	-420	99	.256
1935,36	-400	115	.297
1803,04	-300*	158	.408
1933,34	-380	188	.485
1931,32	-360	308	.795
1929,30	-340	335	.865
1927,28	-320	466	1.203

* above fault + below fault

The dyke stopped at the fault. The fault does not open.

6/13/95 RWT

dikeparm
parmset4

Setup D2KM Dip00b. To = .01 GPa
Tip@ -2140
Problem same as D300 Dip00a except added -2000 to depth. Raised initial dyke tip from -2340 to -2140 to reduced time of calculation—

dikeparm
parmset4

Setup D2KM Dip00c To = .02 GPa
Tip@ -2140 — Problem same as D2KM Dip00c except changed tensile strength of dyke bonds—

6/14/95 RWT

Results of D2km Dip00b To = .01 GPa

Node	Depth	Time Step	Time (s)
1939,40	-2140	36	.065
1937,38	-2120	66	.119
1935,36	-2100	74	.133
1933,34	-2080	83	.149
1925,26	-2000+	89	.160
1931,32	-2060	92	.165
1929,30	-2040	101	.181
1927,28	-2020	114	.205
1803,04	-2000*	234	.420
1799,1800	-1940*	345	.620
1801,1802	-1980*	353	.634
1797,98	-1960*	373	.670
1795,96	-~~1880~~1920*	381	.684
1529,1530	-~~1860~~1900*	~~471~~417	.749
1527,28	-1880*	425	.763
1525,26	-1860*	520	.934
1523,24	-1840*	528	.948

+ below fault * above fault

STOP TIME = 4.5 Sec

dikeparm
parmset4

6/14/95 RWT

Results of D2KMDip00c T_0 = .026
Tip @ -2140 StopTime 3.13 Sec

Nodes	Depth	TimeStep	Time
-1939,40	-2140	62	.111
1937,38	-2120	111	.199
1935,36	-2100	121	.219
1925,26	-2000	137	.246
1933,34	-2080	151	.271
1931,32	-2060	208	.374
1929,30	-2040	254	.456
1927,28	-2020	281	.505

6/15/95 RWT
Summary
T_0 = .026 GPa : The dyke is stopped by fault

T_0 = .01 GPa :
@ Dip = 0° & Depth = 2 km
The dyke propagates past the fault

@ Dip = 0° & Depth = 300 m
The dyke is stopped by fault

Depth4km Dip30a — Setup Depth 4Km Dip = 30° T_0 = .01 GPa

Depth4km Dip30b — Setup Depth 4km Dip = 30° T_0 = .001 GPa
This is to see if dyke can propagate through fault for very low tensile strength —

6/16/95 RWT

Depth4km Dip30a — Results of Depth 4km Dip30a T_0 = .016 Pa

node	Depth	TimeStep	Time
271,272	-4140	47	.065
269,270	-4120	83	.115
267,268	-4100	95	.131
265,266	-4080	111	.151
263,264	-4060	120	.166
261,262	-4040	132	.182
1601,1602	-4000*	141	.195
259,260	-4020	150	.207
257,258	-4000+	156	.215

* above fault + below fault
Fault shifted 5 cm on bottom
Fault remained closed

Depth 4km Dip30b — Results of Depth 4km Dip30b T_0 = .001 GPa

node	Depth	Timestep	Time
271,72	-4140	12	
269,70	-4120	30	
267,68	-4100	37	
265,66	-4080	45	
263,64	-4060	52	
261,62	-4040	59	
1601,02	-4000*	62	
259,60	~~-3980~~ -4020	68	
257,58	~~-3960~~ -4000+	76	
1605,06	-3980	109	
1603,04	-3960	113	
1607,08	-3940	116	
1609,10	-3920	119	
1611,12	-3900	126	
1613,14	-3880	131	
1615,16	-3860	136	
1617,18	-3840	144	
1619,20	-3820	151	

6/16/95 RWT

Results of Depth 4km Dip30b

1621,22	-3800	161
1623,24	-3780	216
1625,26	-3760	220
1627,28	-3740	227
1629,30	-3720	234
1631,32	-3700	236

*above fault + below fault
stoptime = 3.0 s   Δt = 1.442

T_o = .01 GPa
@ Depth 4km Dip = 30°
dyke stopped by fault
T_o = .001 GPa
@ Depth 4km Dip 30°
dyke propagates past fault

Conclusion:
Tensile strength of bond < .01 GPa
for Depth ≤ ~~4~~ 2km & Dip = 30°

Depth 2km Dip 30b — Set up Depth 2km Dip 30b T_o = .001 GPa
To establish min T_o to propagate dyke past fault

Depth 2km Dip 30C — Set up Depth 2km Dip 30C T_o = .0066 Pa
to see if average tensile strength for limestone will propagate dyke past 30° fault.

6/19/95 RWT

Depth 2km Dip30b

Results of Depth 2km Dip 30b T_o = .001

Node	Depth	Timestep	Time
271,72	-2140	10	
269,70	-2120	23	
267,68	-2100	29	
265,66	-2080	34	
263,64	-2060	40	
1601,1602	-2000*	45	
261,262	-2040	47	
259,260	-2020	53	
257,258	-2000+	57	
1603,1604	-1980	90	
1605,1606	-1960	92	
1607,1608	-1940	96	
1609,1610	-1920	100	
1611,1612	-1900	103	
1613,1614	-1880	107	
1615,1616	-1860	110	
1617,1618	-1840	115	
1619,1620	-1820	121	
1621,1622	-1800	126	
1623,1624	-1780	136	
1625,1626	-1760	144	
1627,1628	-1740	223	
1629,1630	-1720	297	

STOP TIME = 3.02 sec   Δt = 1.932 Sec
+ below fault   * above fault

T_o = .001 @ 2km @ 30° Dip
dyke propagates past fault

6/19/95 RWT

Depth 2km Dip 30c

Results of Depth 2Km Dip 30 c T_0 = .006

Node	Depth	Time Step
271, 272	-2140	27
269, 270	-2120	49
267, 268	-2100	56
265, 266	-2080	64
263, 264	-2060	71
1601, 1602*	-2000*	76
261, 262	-2040	80
259, 260	-2020	90
257, 258	-2000+	95
1605, 1606	-1980	320
1603, 1604	-1960	326
1607, 1608	-1940	334
1609, 1610	-1920	337
1611, 1612	-1900	344
1613, 1614	-1880	351
1615, 1616	-1860	359
1617, 1618	-1840	372
1619, 1620	-1820	387
1621, 1622	-1800	397
1623, 1624	-1780	408
1625, 1626	-1760	417
1627, 1628	-1740	~~492~~ 429
1629, 1630	-1720	447

* above fault. + below fault

stop time = 4.0 Sec δt = 1.862

T_0 = .001 GPa
@ Depth 2km Dip 30°
dyke propagates past fault

T_0 = .006 GPa
@ Depth 2km Dip 30°
dyke propagates past fault

6/20/95 RWT

Depth 300m Dip 30d — Setup Depth 300m Dip 30d T_0 = .006 Gpa

Depth 2km Dip 30d — Setup Depth 2km Dip 30d T_0 = .008 Gpa

6/21/95 RWT

Depth 300m Dip 30d @ T = 4.0 Sec

Depth 2km Dip 30d came off with error - fixed overburden mistype - put back on

6/22/95 RWT

Depth 2km Dip 30d @ T = 3.0 Sec

Depth 300m Dip 30d

Depth 300m Dip 30d @ T = ~~5~~ 10.0 Sec

Results of Depth 300m Dip 30d

Time = 5.0 Sec   Max disp = .415 m

Crack Tip depth @ -370 m

Pressure head @ -540 m

Depth	crk wall displacement
370	.05
390	.0625
410	.0750
430	.0875
450	.10
460	.125
480	.138
500	.150

6/22/95 RWT

Time = 10.0 Sec Max disp = .415

Crk Tip depth @ -180 m

Pressure head @ -440 m

Depth	crk wall displacement
190	~~.0125~~ .025
240	.0375
280	.05
300	.0625
340	.0875
360	.10
400	.1375

6/23/95 RWT

Depth 2km Dip 30d @ T= 6.0 Sec

Depth 300m Dip30d @ T= 14.0 Sec

Depth300m Dip30d

Depth300 Dip30d Max disp = .421 @ T=14.0 Sec

Crk Tip depth = -140 m

Depth (m)	Crk half width (m)	Depth (m)	Crk Half width (m)
-90	.0125	-310	.113
-140	.025	-320	.125
-180	.038	-330	.138
-210	.050	-340	.150
-240	.063	-350	.180
-260	.075	-360	.200
-300	.088	-360 pressure head	

Depth 2km Dip30d

Depth 2km Dip30d

Time	Crk Tip depth	Press head	L	Disp
0	-640	-640	0	~~.398~~
1.0	-410	-620	210	.398
3.0	-370	-580	210	.386
5.0	-350	-540	210	.400
6.0	-350	-520	190	.410

6/26/95 RWT

Depth 300m Dip30d @ T= 17.0 Sec

Depth 2km Dip30d @ T= 17.0 Sec

Results of Depth300m Dip30d T_0 = .006 GPa

Time = 17.0 Sec - Crk Tip @ -20m

Pressure head @ -300 m

Depth (m)	Crk Half Width (m)	Depth (m)	Crk Half Width (m)
-70	.038	-320	.25
-110	.050	-350	.29
-160	.063	-400	.32
-200	.075	-460	.36
-220	.088	-570	.40
-260	.100		

There was differential motion along the fault of about 0.1m but the fault remained closed. The dyke propagated past the fault, almost to the surface. The dyke crack above the fault is much thinner than it would be without the fault. Would expect the magma to stagnate at the fault because

1. Above the fault the thin dyke would freeze the magma.
2. the magma is moving due to momentum and not buoyancy at this depth -
3. The fault is closed but able to move differentially in the horizontal direction.

6/26/95 RWT

Results for Depth 2km Dip 30d T=17 Sec

Time (sec)	~~Disp Crk Tp~~ Depth (m)	Depth Pres (m) head	Wall Dispacement (m)
7.0	-2030	-2200	.40
8.0	-2030	-2180	.413
9.0	-2010	-2160	.413
10.0	-2000	-2140	.413
12.0	-1960	-2100	.413
14.0	-1920	-2060	.415
16.0	-1860	-2020	.420
17.0	-1740	-2000	.425

T=17 Sec - Crack width

Depth (m)	Crk half width (m)	Depth (m)	Crk half width (m)
-1760	.025	-2020	.210
-1810	.038	-2050	.250
-1860	.050	-2090	.287
-1910	.063	-2140	.325
-1940	.075	-2240	.362
~~-2000~~ -1970	.088		
-2000	.10		

The results from calc of dip 30° at depth of 2 kilometers are very similar to the calc at 300 m depth. The crack propagated ~ 240 m past the fault but the width of the crack is very thin above the fault. The fault showed differential motion of about 0.1 meters.

In both cases the dyke propagates past the fault for both Tensile stregth bonds of .006 and .008 GPa.

6/27/95 RWT

Review references on tensile strengths.

Ref "Elastic Fracture and Flow"
by J.C. Jaeger 1964
Barnes and Noble - Publ.
gives 40-bars tensile strength for limestone -

Table III page 75 above reference

Rock	Tensile strength (bars)	
Granite	40	.004 GPa
Marble	60	
Limestone	40	
Sandstone	20	.00

Ref "Handbook of Physical Constants"
by Sydney P. Clark 1966
Publ - The Geological Society of Am.

Table 11-8 Page 279

Rock	Tensilestrength (bars)
Sandstone	8 to 34
Shale	1

Ref "Laboratory Investigation of Containment of Underground Explosion" 1983
by J.C. Cizek
Ed Florence

	Rock	Tensile Stgth
Page 54	Rock matching Grout - Tuff	4 bars

6/27/95 RWT

Call Larry McKagoe of SRI
Informed him of the following

- Absent the fault, the dyke propagates almost independent of the bond tensile strength less than 0.03 GPa
- Fault of dip 30° stops dyke propagation unless tensile bond strength is less than .01 GPa
- Data I have suggest the tensile strength is on the order 40 bars (.004) GPa
- Calc for 30° fault using T_0 = .006 or .008 GPa yield a very thin crack about the fault. The faults show differential motion of 0.1 m and fault remain closed
- Suggest we continue study using T_0 = .004 GPa – McKague agreed
- Meeting scheduled at SRI for July 20 & 21, 1995 –

6/28/95 RWT

New calculational Plan

- Depth 2 km Dip 30 — Generated 6/28/95
- Depth 300 m Dip 30 — Generated 6/28/95
- Depth 2 km Dip 50
- Depth 300 m Dip 50
- Depth 2 km Dip 70
- Depth 2 km Dip 40 — Generated and running
- Depth 1 km Dip 30
- Depth 300 m Dip 40
- Depth 300 m Dip 70

6/29/95 RWT

Generated Depth 2 km Dip 50

Generated Depth 300 m Dip 50

6/30/95 RWT

Generated Depth 2 km Dip 70

Generated Depth 1 km Dip 30

7/3/95 to 7/8/95 Vacation RWT

7/10/95 RWT

Depth 2 km Dip 40 a — Complete
Depth 2 km Dip 30 a — Completed
Depth 300 m Dip 30 a — Completed
Depth 2 km Dip 50 a — Completed
Depth 300 m Dip 50 a — Completed
Depth 2 km Dip 70 — @ 8.5 Sec
Depth 1 km Dip 30 — @ 4.5 Sec

7/10/95 RWT
Results of depth 2 km dip 40a
Crack tip seemed to propagate smoothly across the fault.

Time	Crack tip depth
0	-2340
5 s	-2070
10 s	-2000
15 s	-1880
19 s	-1800

At 19s the dyke crack width vs depth

Depth	dyke ½ width
-1740	.025
-1830	.050
-1880	.075
-1920	.100
-1950	.125
-1970	.150
-2000	.225
-2020	.250
-2040	.275
-2060	.300
-2090	.325
-2170	.350
-2340	.43

x	fault disp Δy	
10	-.025	low
30	.0	low
-30	-.025	low
-10	+.10	Top
+40	+.125	Top

x	fault disp Δx	
-10	-.2	Top
-30	-.175	Top
-80	-.175	Top
+20	+.175	
+40	+.150	
+70	+.100	
+100	+.075	

The dyke about the fault opened about 15 cm. The fault opened about 10 cm at the dyke and closed about 40 m from the dyke.

7/10/95 RWT
Results of depth 2 km dip 30a
19 Seconds Dyke crack ½ width vs depth

Depth	dyke ½ width	Δx	fault Δx	
-1750	.025	20	.20	low
-1800	.038	40	.175	low
-1850	.050	60	.150	low
-1890	.063	90	.125	low
-1930	.075	130	.100	low
-1960	.088	170	.075	low
-2020	.225	210	.050	low
-2040	.250			
-2060	.275	x	fault Δy	
-2090	.300	20	-.025	low
-2130	.325	40	0.	low
-2180	.350	70	+.025	low
-2260	.375	120	+.050	low
-2340	.45			
		40	+.125	top

The dyke about the fault opened about 10 cm and the fault opened about 3 cm near the dyke.

Results of depth 2 km dip 50a

Grid at -1700 m depth shows severe distortion for unknown reason—

Same error is in depth 2 km dip 70a

Haven't found the error — !!!

7/11/95 RWT

Both depth 2 km dip 50 and dip 70 had the zoning grid to the surface. A low stress region is developed in zones near (x=0 y=-1700 z=0) dyke bond at -1720 depth broke early, (before 5 sec). Don't yet understand the distortion at -1720 m. Pressure in that zone are at about overburden - Source deck looks ok??

Results of depth 300m dip30a

7/12/95 RWT

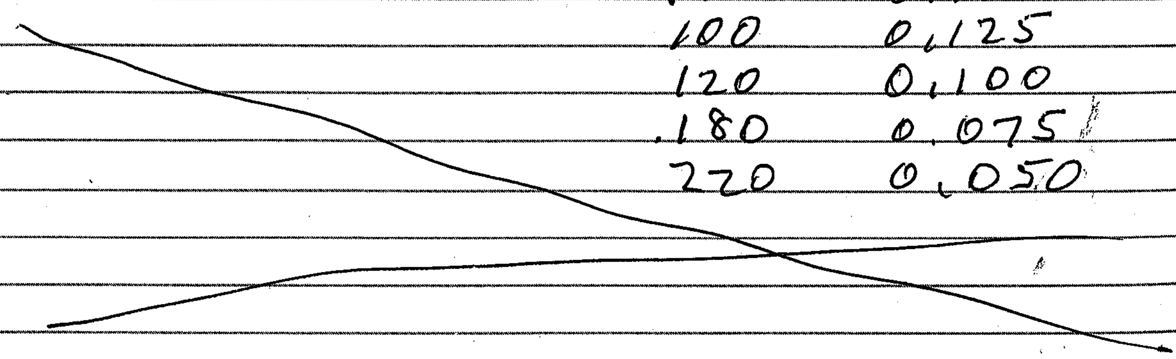
Results of depth 300m dip30a T=19 Sec

Depth	dyke ½ width (m)
Surface	> 0.025
-110	0.050
-190	0.075
-240	0.100
-290	0.125
-320	0.250
-370	0.300
-430	0.350
-560	0.400
-640	0.440

x	fault Δy
20	-0.050
50	-0.025
80	0.0
120	+0.025
160	+0.050
220	+0.075

low

x	fault Δx
30	+0.20
50	0.175
70	0.150
100	0.125
120	0.100
180	0.075
220	0.050



7/12/95 RWT

Have not found error that caused depth 2 km - dip 50 and dip 70 to have a distorted grid. depth 2 km - dip 30 and dip 40 show no sign of distortion of the grid. All 4 calculations modeled the region from the surface to a depth of 2700 m in the same manner. ???

Regenerated depth 2 km dip 50 b. Eliminated section of grid distortion at 1700 m. Modeled grid from -1700 to -2700 m depth. Everything else the same.

7/13/95 RWT

Have not been able to find error. New calc depth 2 km dip 50 b at 5 sec and looks good so far.

Results of Depth 300 dip 50a

Depth	dyke ½ width	Depth	dyke ½ width
surface	> 0.025	400	0.325
80	0.050	440	0.350
140	0.075	490	0.375
180	0.100	580	0.400
220	0.125	640	0.430
250	0.150		
270	0.175		
290	0.200		
320	0.225		
340	0.275		
380	0.300		

7/13/95 RWT

Results of Depth 300 dip 50a continued

x	faults y	x	fault Δx
0	< 0.025	10	0.20
120	< 0.025	50	0.10
		80	0.075
		120	0.050
		170	0.025

7/14/95 RWT

Calc depth 2 km dip 50 b at 10 sec. Still looks good.

Generated depth 2 km dip 70 b similar to depth 2 km dip 50 b.

ON 7/20/95 B. MAGRITO REVIEWED This document And Found IT IN compliance with QAP-001. [signature] 7/20/95

7/17/95 RWT

Depth 2 km Dip 50 b completed at 19 s

Depth 2 km Dip 70 b @ 6.3 seconds

7/24/95 RWT

Met with SWRI Personnell for discussion on Dyke-Fault interaction

Larry McKague x 5183

Goodluck Ofoegbu x 6641

Dave Farrill x 6082

Chuck Connor x 6649

Dave Farrill gave me NRC report that these calculations were to be compared too.

"NRC High-Level Radioactive waste research at CNWRA July-Dec 1993.

edited by Budhi Sagar Feb 1994

Page 10-1 to 10-26

Change in scope of project —

1. Only two depths - 2 km and 5 km
2. Three fault dips - 30°, 50° & 70°
3. Use shear resistance rather than angle of friction on faults
4. Move fixed boundaries to x = ± 1500 m
5. Use elastic media E = 32.5 ν = 1/3

7/24/95 RWT

Elastic properties obtained from Goodluck Ofoegbu

Machines down — no computer effort —

7/25/95.

Setup parameter study for new study parameters.

width / wide1500 ≡ w1500dip00a
depth 2000 m tip @ -2500 m
pressure 0.01 GPa
fixed boundaries @ ± 1500 m
Young's modulus E = 32.5 GPa
poisson's ratio ν = 0.3333
density ρ = 2.70
dyke tensile strength = .005 GPa

@ 0.5 Sec disp ~ 3.5 m, No slip on fault.

- found error in Ingrid generator - does not give correct coeficient of fration to dyna generator — Modified dyna3d generator - Sliding interface card
Columns - 16-25, 26-35, 36-45.

Set up w1500dip00b with dyke pressure = 0.005 GPa

7/25/95 RWT

w1500dip00b @ 5 Sec
dyke displacement = 3.5 m —

Set up w1500dip00c with
dyke pressure = 0.001 GPa

dyke displacement @ 0.5 Sec = 3.29 m

Set up w1500dip00d with
dyke pressure = 0.0005

dyke displacement @ 0.5 Sec = 3.1 m

Something wrong!!!
No overburden pressure in any of
the w1500 ... calculations!

Problem is using Material #1 elastic —

Changed to Material #5 elastic-
plastic-soil — where overburden
works

Given E = 32.5 $\nu = 0.3333$

Shear Modulus $G = E/2(1+\nu)$

Bulk Modulus $K = E/3(1-2\nu)$

K = 32.5 GPa G = 12.2 GPa

C_p = 4.25 m/msec C_s = 1.225 m/msec

7/26/95 RWT

Developed compressibility curve where

$Mu = P/K \qquad \frac{V}{V_0} = \frac{1}{1+Mu}$

& $\varepsilon_v = \ln \frac{V}{V_0}$.

P	Mu	V/Vo	ε_v
0	0	1.0	0.0
.1	0.003077	0.996932	-0.0030722
.3	0.009231	0.990853	-0.0091884
.5	0.015385	0.984849	-0.0152675

Set up w1500p01 with dyke
pressure = 0.01 GPa and
new material model as elastic

Overburden pressure ok

Set up w1500p005 with dyke
pressure = 0.005 GPa

7/27/95 RWT

Results of w1500p01

Time	Wall disp
0	0
.5	0.222
1.0	0.540
1.5	0.385
2.0	0.356

G = 12.2 GPa

Ramp = .5

7/27/95 RWT

Results of W1500p005

Time	Wall disp
0	
0.5	.110
1.0	.270
1.5	.197
2.0	.179

G = 12.2

Ramp = .5

Setup eosg12 with

p = .0085 GPa

G = 12.2 Gpa

Ramp = 4.0

Set up eosg20 with

p = .01 GPa

G = 20.0 GPa

Ramp = 4.0

~~7/28/95~~ 7/31/95 RWT

Results of ~~to~~ eosg12

Time	Disp
1	
2	.144
3	
4	.312
5	.302
6	.309
7	.309
8	.312

Ramp remove ocilations

Pressure .0085 to low for G = 12.2

Results of eosg20

Time	Disp
1	
2	
3	
4	
5	
6	-.239
7	-.259
8	-.251

Ramp reduced occ.

Pressure to low by factor of 2

Setup eosg20a with

p = .02 GPa

Ramp = 2.0

G = 20.0 GPa

8/1/95 RWT

Results of EOSg20a

Time	Wall disp	
1		
2	.577	Ramp = 2.0 too fast
3	.537	
4	.564	ρ = .02 GPa almost
5	.640	ok but a little too large

Set up EOSg20de

ρ = 0.016 GPa
ramp = 4.0
G = 20 GPa

8/2/95 RWT

Results of EOSg20de

Time	Wall disp	Tip depth
0	-	
3.0	.321	-2010
3.5	.391	-2010
4.0	.438	-2010
4.5	.442	-2010
5.0	.436	~~-20~~ -1990
5.5	.447	-1990
6.0	.434	-1990
6.5	.434	-1990
7.0	.440	
9.0	.439	
11.0	.449	

8/3/95 RWT

Noticed on EOSg20de that the slip line modeling the fault did not break as expected –

Width of dyke just right & stable –

→ Use dyke pressure = 0.016 GPa and ramp = 4.0

Set up Slip1 with different slips id no. where slips cross each other —

8/4/95 RWT

Results of Slip1

Tip of crack grew evenly across fault to depth -1910 m where horizontal fault at -2000m

Looks good ready to run —

Set up dip 30 c depth 2 km
fault friction = 1.2 = tan 50°
dyke pressure = 0.016 GPa
Ramp = 4.0 Sec
ρ = 2.7 gm/cc
E = 48.7 GPa
G = 19.5 GPa
K = 32.5 GPa
ν = 0.25
fix boundaries at ± 1500
Tensile strength across dyke = .01

8/7/95 RWT

dip30c depth2km still running –

8/8/95 RWT

dip30c depth2km complete

set up dip50c depth2km with same parameters as dip30c, except depth set at 2000 m and fault dip at 50° –

8/9/95 RWT

Results of Depth2km dip30c

Crack Tip propagation

Depth	Time	Depth	Time
-2340	.551	-2000	12.0
-2320	1.03	-1980	12.1
-2300	1.06	-1960	12.11
-2280	1.15	-1940	12.13
-2260	1.19	-1920	12.14
-2240	1.33	-1900	12.15
-2220	1.35	-1880	12.15
-2200	1.43	-1800	12.20
-2180	1.45	-1700	12.26
-2160	1.48	-1600	12.33
-2140	1.76	-1520	12.42
-2120	1.79	-1500	13.82
-2100	2.15	-1457	13.89
-2080	2.17		
-2060	2.64		
-2040	3.43		
-2020	3.45		
-2000	3.47		

8/10/95 RWT

Results of Depth2km dip30C

Dyke wall displacement

Depth	Disp (L)	Depth	(R) Disp
-1550	-.0625	-1600	+.0625
-1680	-.0938	-1720	+.0938
+1770	-.1250	-1870	+.1250
-1880	-.156		
-1920	-.188	-2040	+.275
-1970	-.219	-2080	+.300
		-2120	+.325
-2060	-.325	-2180	+.350
-2120	-.350	-2270	+.375
-2260	-.375	-2340	+.400
-2480	-.400		

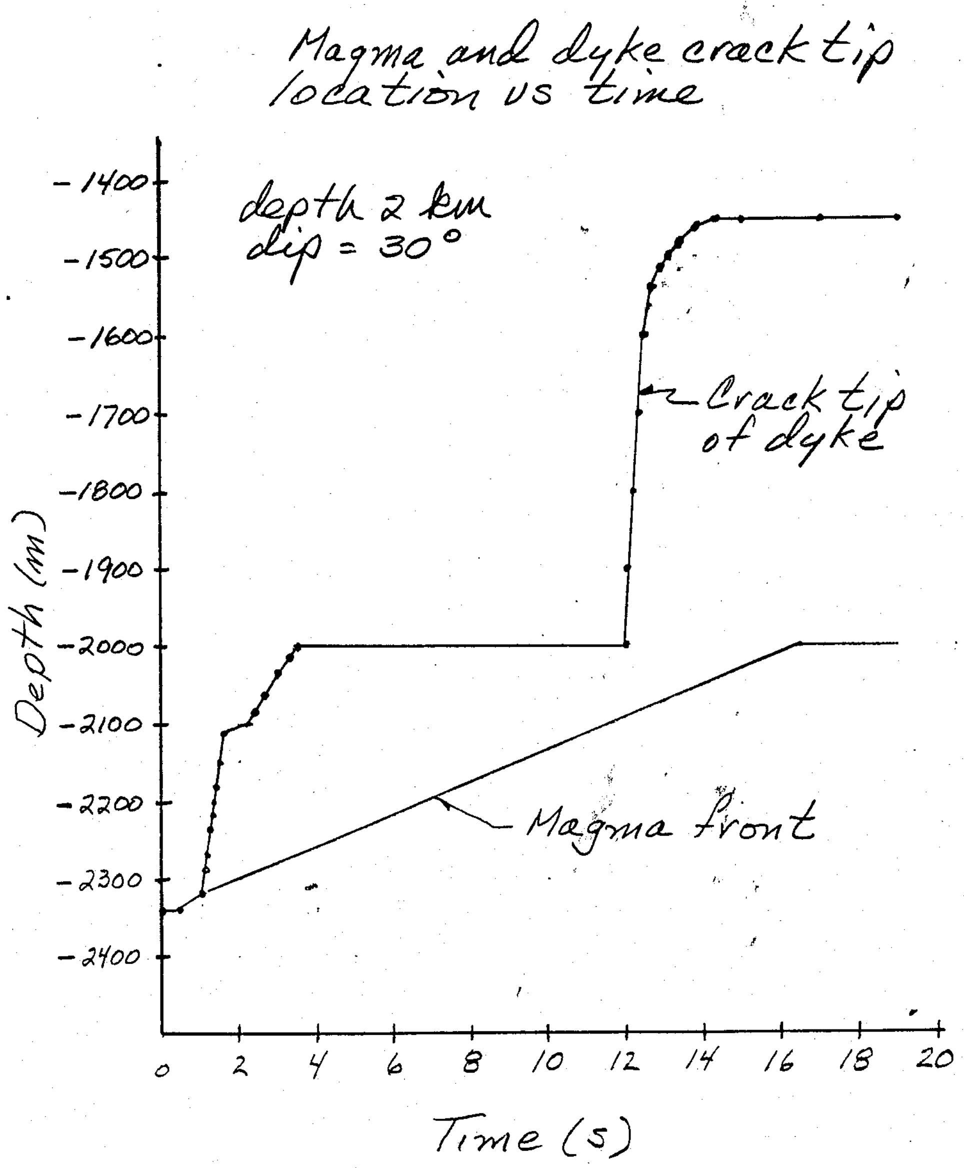
fault displacement

Horiz Dist	Horiz Disp
20	.250
90	.219
160	.188
230	.150

fault remained closed

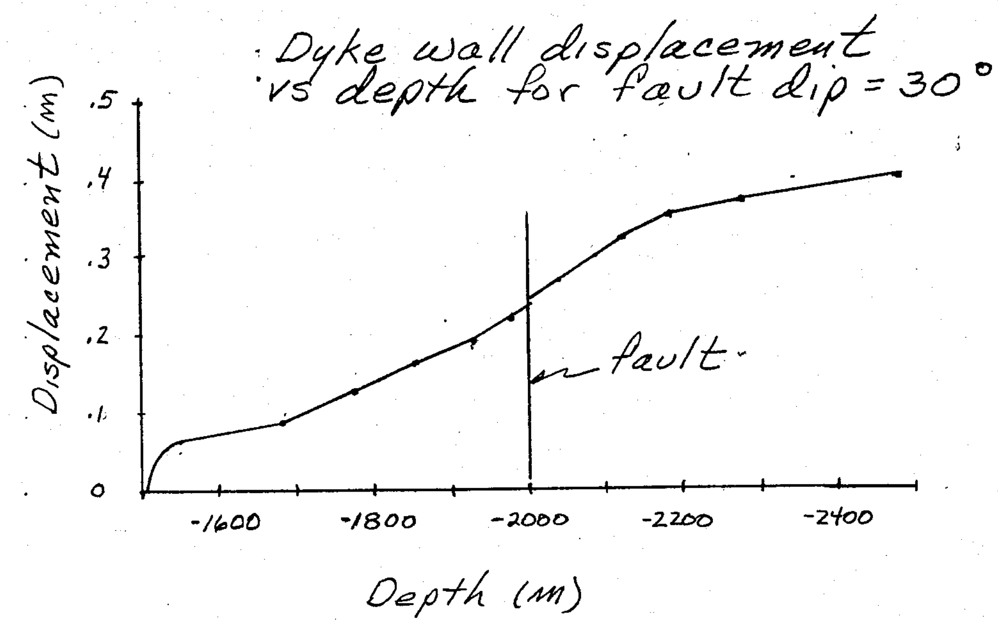
8/11/95 RWT

Below is a plot of crack tip propagation and magma propagation vs time. for Depth 2km dip 30C



8/11/95 RWT

Below is plot of dyke wall dispecement vs Depth for Depth 2 km dip 30C



~~8/12~~

Calc depth 2km dip 50C still running. Time at 11.5 Sec - Crack tip at fault.

8/14/95 RWT

Depth 2 km dip 50C completed.

Set up Depth 5 km dip 50C

8/15/95 RWT

Results of Depth 2 km dip 50C

Crack Tip propagation

Depth	Time	Depth	Time
-2340	.526	-2160	1.474
-2320	.953	-2140	1.817
-2300	.994	-2120	1.894
-2280	1.069	-2100	2.182
-2260	1.095	-2080	2.231
-2240	1.168	-2060	2.431
-2220	1.244	-2040	3.502
-2200	1.333	-2020	7.755
-2180	1.408	-2000	7.762

Dike displacement

Depth	Disp (L)	Disp (R)
-1680	-.031	
-1780	-.063	-.031
-1850	-.093	-.063
-1900	-.125	-.093
-1950	-.156	-.125
-1990	-.188	
-2040	-.250	
-2070	-.275	
-2120	-.300	
-2230	-.320	

8/16/95 RWT

Results of Depth 2 km dip 50C

Dike Displacement

Depth	Disp (R)
-2020	+.220
-2060	+.250
-2090	+.275
-2140	+.300
-2190	+.325
-2260	+.350
-2360	+.375

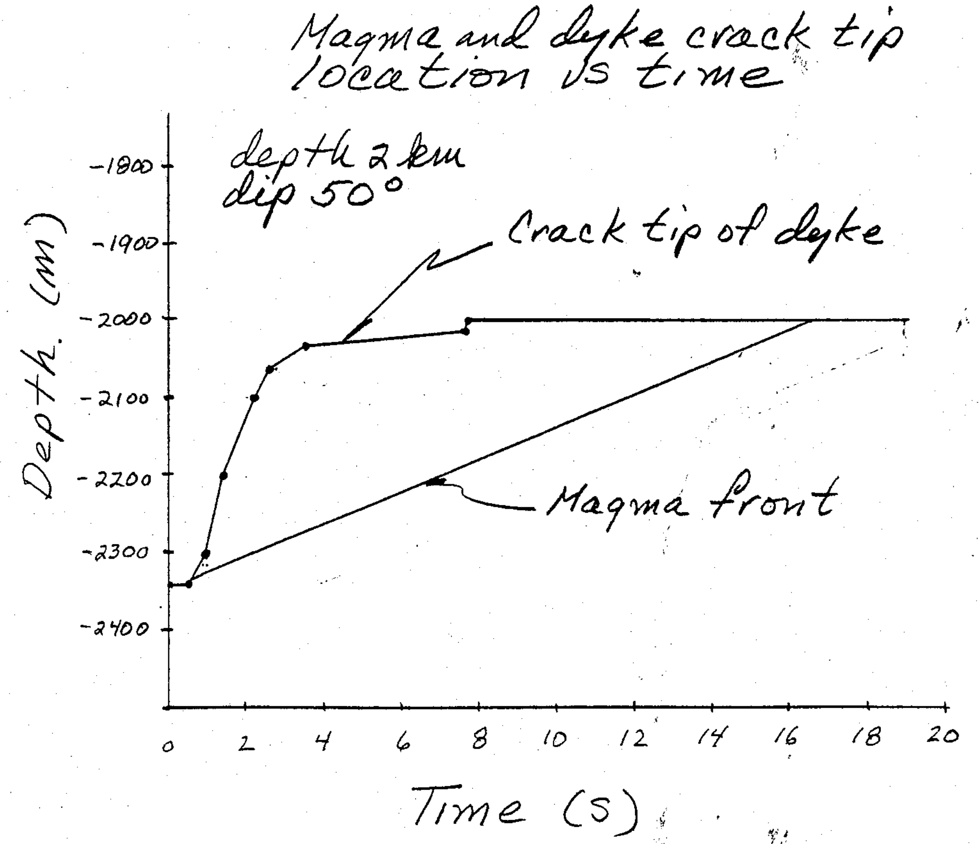
Fault Displacement

Horiz Dist	Disp Top	Disp Bottom
40	-.125	+.188
80	-.093	+.156
120	-.063	+.125
160	-.031	+.093
180	.0	.0

Fault opened up & dyke path showed no sign of crack propagation above the fault.

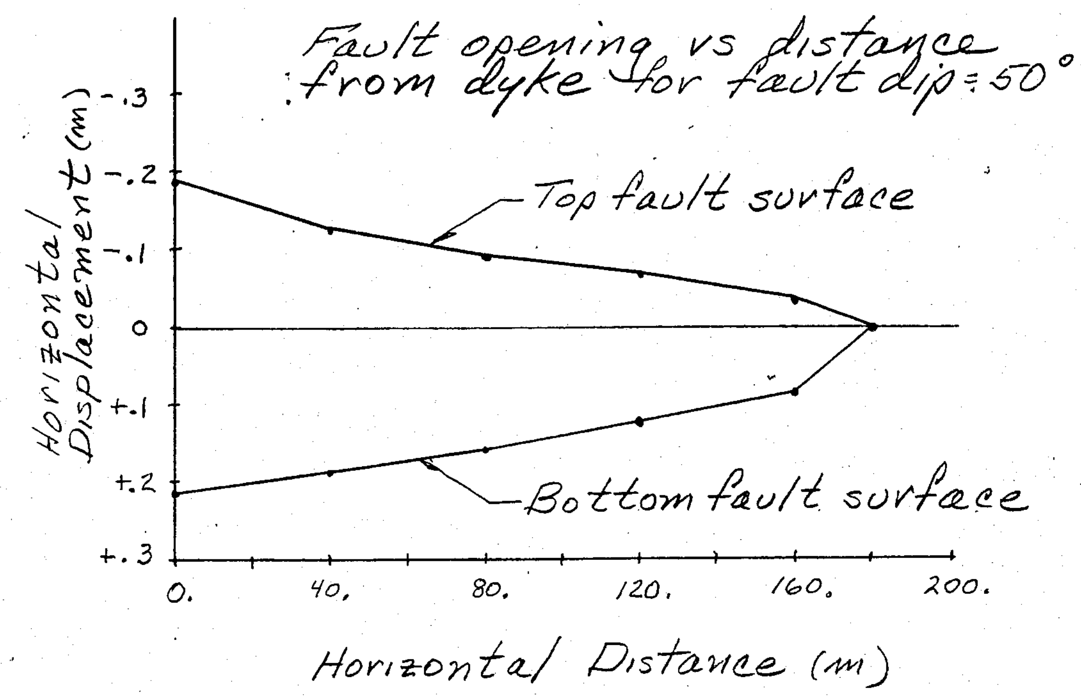
8/18/95

Below is a plot of Magma & dyke tip propagation for case Depth 2 km, dip 50c



8/18/95

Below is a plot of the fault displacement vs horizontal distance for Depth 2 km dip 50c



The top of the fault moved to the left and the top of the fault moved to the right creating a gap of ~.4 m at the intersection point between the dyke and the fault

8/21/95 RWT

Depth 5 km Dip 50c complete

Set up Depth 2 km Dip 40c

8/22/95 RWT

Depth 2 km Dip 40c at 3.79 Sec

Discussion with Larry McKague

Informed McKague of results of calc Depth 2 km Dip 30c and Depth 2 km Dip 50c and Depth 5 km Dip 50c. Agreed that ~~not~~ no point in doing calc Depth 5 km Dip 30c and Depth 2 km Dip 70c as they would show same results as Dip 50c. Agreed that Depth 5 km Dip 30c could be skipped cause it would show same results as Depth 2 km Dip 30c. Decided on change in plan corresponding to option 2 of enclosed FAX to McKague –

Plan

Keep same tensile strength = .016Pa and same coef of friction = 1.2

Calc

1. Depth 2 km Dip 40 degrees
2. Depth 1 km Dip 30 degrees
3. Depth 5 km Dip 40 degrees
4. Depth 1 km Dip 40 degrees (Dependent on results from 2)

8/22/95 RWT

Results from Depth 5 km Dip 50 c

Crack tip propagation

Depth (m)	Time (Sec)		Depth (m)	Time (Sec)
-5340	.53		-5120	2.24
-5320	.95		-5100	3.29
-5300	1.05		-5080	3.40
-5280	1.26		-5060	7.40
-5260	1.54		-5040	7.49
-5240	1.63		-5020	13.29
-5220	1.83		-5000+	13.30
-5200	1.91		-5000*	17.14
-5180	1.98		-4085	18.61
-5160	2.05	(-4125)	~~[illegible]~~	18.64
-5140	2.13			

\+ below fault
* Above fault

Fault Displacement

Horiz distance along fault = X

Top of fault

X	Disp
0	-.112
40	-.088
60	-.075
80	-.063
120	-.050
160	-.038
180	-.025

bottom of fault

X	Disp
0	+.125
40	+.100
70	+.075
100	+.050
160	+.025

8/23/95 RWT

Depth 2 km Dip 40c @ time = 8.9 Sec

Results of Depth 5 km Dip 50c

Dyke Displacement

Left side		Right side	
Depth	Disp	Depth	Disp
-5000	-.137	-5010	+.125
-5020	-.150	-5050	+.150
-5030	-.162	-5090	+.175
-5040	-.175	-5140	+.200
-5070	-.188	-5190	+.225
-5110	-.200	-5270	+.250
		-5360	+.275

Dip 50c @ depth 5 km showed a open fault but some late time cracking on the dyke. This could be a marginal situation where a small change in one of the variables (ie, less tensile strength or greater friction along fault) could have caused the dyke to propagate past the fault

8/24/95 RWT

Depth 2 km Dip 40c @ time 13.1 Sec

8/25/95 RWT

Depth 2 km Dip 40c complete

Results from Depth 2 km Dip 40c

Tip Propagation

Depth	Time
-2000	3.55 S
-2000	14.66
-1940	
-1900	15.05
-1800	+15.09
-1700	15.16
-1600	15.23
-1500	15.31
-1396	15.59
-1367	15.61

Depth 2 km Dip 40c propagated the dyke past the fault. Where as Depth 2 km Dip 30 fracture started past the fault a 12 seconds. Depth 2 km Dip 40c started past the fault at 14.5 sec. There may be boundary effects where the fault slips and opens until the fault termination point is reached and tensile stress is then put on the dyke.

Set up Depth 1 km Dip 40c

8/28/95 RWT

Depth 1 km Dip 40°c at 12.1 Sec

8/29/95 RWT

Depth 1 km Dip 40c complete

Results from Depth 1 km Dip 40c
Dyke tip propagation

Depth	Time	Depth	Time
-1340	.54	-1000+	6.69
-1300	1.11	-900	18.54
-1200	1.36	-800	18.59
-1100	2.15	-700	18.65
-1000+	3.42	-600	18.71
		-500	18.79
		-356	19.00

The results of Depth 1KM Dip 40C is consistent with the ~~last~~ results of 2 km - 30° and 2 km - 40° where the dyke propagated past the fault.
Based on the theoretical analysis in the paper edited by B Sagar Feb 94, the calculation of depth 2 km - 30° dip is most likely to propagate past the fault, while 1 km - 40° is the least likely to show the dyke ~~has~~ propagated past.

Calc	time dyke fracture
2 km - dip 30	12.0 s
2 km - dip 40	14.6 s
1 km - dip 40	18.4 s

8/30/95 RWT

The results of the last 3 calc of 2 km - 30°, 2 km - 40° and 1 km - 40° show the dyke propagating up to the fault, then stopping for 8 to 15 seconds before continuing on past the fault. The fault slips and opens until the slippage reaches the termination of the fault at X = 240 m. This acts as if the fault jammed which allowed the dyke to continue propagating at a later time. To check this out - will rerun 2 km - 40° dip calculation with same friction coef and tensile strength but a extended fault to X = 600 m.

Set up Depth 2 km - dip 40 d. with extended fault.

8/31/95 RWT

Depth 2 km - dip 40 d at 4.0 Sec

9/1/95 RWT

Depth 2 km - dip 40 d at 8.0 Sec

9/1/95 RWT

Need to reconsider the fault model. Instead of a coefficient of friction to resist movement along the fault, use a model representing a healed fault where asperities need to be sheared off in order to slide with friction.

1. Set tensile strength of fault to zero
2. Set shear strength of fault to unconfined compressive strength of typical gouge material
3. Set coef of friction = tan 50°

The problem with this model is that the effects of the overburden stress due to increased depth is removed.

9/5/95 RWT

Depth 2 KM Dip 40 d complete

Dyke Tip Growth

Depth	Time (s)
-2340	.551
-2300	1.057
-2200	1.403
-2100	2.154
-2040	2.739
-2020	3.516
-2000	3.502

9/5/95 RWT

Dyke Tip Growth

Depth (m)	Time (s)
-2000	15.34
-1960	18.22
-1900	18.30
-1800	18.34
-1700	18.42
-1600	18.48
-1500	18.55
-1424	18.64

Depth 2 KM Dip 40 d showed the dyke propagated pass the fault. Thus the extended fault of 40d show the same result as 40C. Comparison of the timing shows the dyke fracture above the fault occurred approximately 2 sec in ~~later than~~ 40d than 40C

9/6/95 RWT

Found error in Depth 2 km Dip 40 d. In Dip 40 C slip line 10 ~~is~~ lied on x y z plane at x = 240 m. When the fault was extended past 240 m to 600 m slipline 10 was left at 240 m. On initiation the fault slipped such that a node ~~at~~ on the upper side of fault and left of slip 10 tied with a node on the lower side of fault and right of slip 10. Thus the fault was not a true slip surface where a tied-node bonded the fault at x = 240 m

9/6/95 RWT

After the dyke propagated past the dyke the bond was in tension and caused the ~~f~~ upper right hand side of the dyke-fault intersection to open?? It may has also allowed the dyke to propagate past the dyke.

Will rerun

Set up Depth2KM Dip 40Z when slip10 was replaced with 2 slips - one on each side of the fault.

Also running the ~~magma~~ from -2340 to the intersection does not seem to ~~~~ meet the goals. Originally thought the curvature of the dyke ~~near~~ the tip as it propagated into the intersection might effect the results. The dyke rapidly moves to the fault intersection and stops, the fault slips and all trace of curvature in the dyke is lost.

Depth 2km Dip40Z will have the pressure over the entire dyke from the intersection downward. It take 4 sec to come to full pressure. Expect the dyke to propagate past the dyke about 5 sec if the results of Dip40d are accurate -

9/7/95 RWT

Depth 2km Dip40Z running @ 3.6 Sec

9/8/95 RWT

Depth 2km Dip40Z complete @ ~~$~~7.0 Sec

Dyke initialed above fault @ 4.8 Sec

Tip Propagation

Depth	Time
-1980	4.83
-1900	4.91
-1800	4.95
-1700	5.10

Dyke Displacement

Depth (m)	Disp (m)	Depth	
-1560	-.05	-2000	+.250
-1650	-.075	-2050	.275
-1740	-.10	-2100	.300
-1820	-.125	-2140	.325
-1880	-.150	-2200	.350
-1940	-.175	-2300	.375
-1970	-.200	-2420	.400
-2020	-.225		
-2060	-.300		
-2130	-.325		
-2220	-.350		
-2320	-.375		
-2420	-.400		

Fault ~~90~~ X(m)	bot disp (m)
90	.2
140	.175
200	.150
260	.125
320	.100
400	.075
500	.050

9/8/95 RWT

Setup Depth 2 km Dip 30 d as a redo of Dip30c with extended fault.

9/11/95 RWT

Depth 2 km Dip 30 d complete

~~-error on fault slip-~~

Fixed & put back on

9/12/95 RWT

Depth 2 km Dip 30 d @ 4.1 Sec

9/13/95 RWT

Machine Down ////
. . . .
Restart

Depth 2 km Dip 30 d @

9/14/95

Depth 2 km Dip 30 d @ 3.9 Sec

9/15/95

Depth 2 km Dip 30 d complete

9/15/95 RWT

Results of Depth 2 km Dip 30 d

Dike displacement

Depth	Disp-Left	Depth	Disp-right
1490	-.025	1490	.0125
1530	-.038	1520	.025
1580	-.05	1580	.0375
1640	-.0625	1660	.05
1690	-.075	1740	.0625
1740	-.088	1840	.075
1780	-.1	1940	.0875
1810	-.112		
1840	-.125	2010	.025
1880	-.138	2040	.0275
1910	-.15	2100	~~.3 .03~~ .3
1930	-.162	2160	~~.0325~~ .325
1950	-.175	2240	.35
1970	-.188	2330	.375
2000	-.2	2430	.4
2050	-.3		
2120	-.325		
2200	-.35		
2300	-.375		
2440	-.4		

Fault Bot x		Top x	
	~~.22~~		
40	.225	110	.0875
100	.2	240	.075
170	.175	350	.0625
260	.15	500	.05
350	.125		
430	.1		
510	.075		

Dyke propagated past fault to 460 above fault. Dike entrance above fault > 0.2 m

Setup Depth 2 km Dip 70 c

9/18/95 RWT
Depth 2 km Dip 70c at 4 Sec -

9/19/95 RWT
Depth 2 km Dip 70c complete -

Results

Dike displacement -

Depth	Disp Left	Disp Right
+1480	-.05	-.05
+1550	-.075	-.075
+1620	-.1	-.1
1680	-.125	-.125
1750	-.15	-.15
1825	-.175	-.175
1900	-.2	-.2
1920	-.225	-.225
1960	-.25	-.25
2000	-.3	-.275
2025	-.325	x
2050	-.35	-.3
2075	x	-.325
2100	-.375	x
2120	x	-.350
3500	-.428	-.427

fault displacement

X Top	Disp	X bot	Disp
0	.305	0	.258
10	.282	10	.235
20	.258	20	.211
28	.235	40	.188
35	.211	70	.164
40	.188	80	.141
55	.164	100	.117
80	.141	120	.094
120	.117	140	.07
140	.094	160	.047
160	.070	180	.023
170	.047	200	0
180	.023		
200	0		

9/20/95 RWT

Depth 5 km Dip 70c @ 25sec

9/21/95 RWT
Depth 5 km Dip 70c complete

Dike displacement

Depth	Disp	Depth	Disp
4625	0	4625	0
4725	-.1	4650	-.025
4850	-.125	4775	-.05
4925	-.15	+4700	-.075
4975	-.175	+4725	-.1
5000	-.2	4850	-.125
5050	-.225	4925	-.15
5075	-.25	5000	+.225
5100	-.275	5050	+.25
5150	-.3	5075	+.275
5325	-.325	5225	+.3
5500	-.35	5350	+.325
6500	-.45	5525	+.35
		6500	+.45

Fault

bot x	Disp	Top x	Disp
0	+.225	0	-.15
20	+.2	40	-.125
40	+.175	60	-.1
60	+.15	80	-.075
80	+.125	100	-.05
100	+.1	120	-.025
180	0	140	0
200	0	200	0

Fracture occurred on dyke at 4110 m depth and propagated to 4625 depth

9/21/95 RWT

Check calc Depth 5 km Dip 50 c and it also had dike failure at Depth 4063 m. Checked all Depth 2 km Calc and none had dike failure at 1000 m. ???

Set up Depth 5 km Dip 30 z Zoned to surface. Suspect Non reflective boundary may have caused tensile fracture.

9/22/95 RWT

Depth 5 km Dip 30 z at 3 sec

Set up Depth 5 km Dip 40 c
Kept NON-reflective boundary @ 3800 depth

9/25/95 RWT

Depth 5 km Dip 30 z - complete

Depth 5 km Dip 40 c - complete

Results - Dip 40 c had dike failure at ~~406~~ 4117 m depth which then propagated downward to the fault. Why - failure ???
Must be non reflective boundary

9/25/95 RWT

Results for Depth 5 km Dip 30 z

Dike displacement

Depth	Disp	Depth	Disp	Depth	Disp
+4580	-.05	+5000	-.325	5000	.28
4720	-.075	+5050	-.35	5040	.3
4820	-.1	5160	-.375	5070	.325
4900	-.125	5240	-.4	5120	.35
4940	-.15	5360	-.425	5170	.375
4980	-.175	5460	-.45	5240	.4
		6500	-.47	5320	.425
				5480	.45
				6500	.505

fault

top x	Disp	bot x	Disp
0	-.175	0	.280
30	-.15	10	.275
80	-.125	60	.25
150	-.1	120	.225
250	-.075	180	.2
345	-.05	240	.175
480	-.025	300	.15
560	0	380	.125
600	0	460	.1
		520	.075
		600	.05

⇒ Dip 30 z failed at depth 4063 to 4197 ??

Set up Depth 5 km Dip 50 z
Grid same as Dip 50 c except zoned to surface. Dike pressure set at 0.019 GPa

9/26/95 RWT
Depth 5 km Dip 50 Z @ 2.8 Sec

9/27/95 RWT
Depth 5 km Dip 50 Z complete

Results of Dip 50 Z
Dike displacement

Depth	Disp	Depth	Disp
4460	-.075	4540	.1
4600	-.1	4780	.075
4740	-.125	4850	.05
4820	-.15	4900	.025
4900	-.175	4940	0
4980	-.2	4970	-.025
5000	-.21	5000	0.26
5080	-.35	5040	0.275
5250	-.375	5080	0.3
5360	-.4	5120	0.325
5460	-.425	5190	0.35
6500	-.49	5260	0.375
		5370	0.4
		5450	0.425
		6500	0.476

fault

top x	Disp	bot x	Disp
0	-.025	0	0.26
40	0	10	0.25
80	0.025	40	0.225
120	0.05	60	0.2
180	0.075	90	0.175
200	0.1	120	0.15
		160	0.125
		200	0.1

=> Dike failure @ 4091 depth and propagated downward to fault. ??

9/27/95 RWT

Setup Depth 5 km Dip 40 Z
Zoned to surface, extended fault to 600 m, dike pressure .0196 Pa

9/28/95 RWT

Depth 5 km Dip 40 Z @ 3.0 Sec

9/29/95

Depth 5 km Dip 40 Z Complete

=> Dike failed first @ 4110 m depth to 4063 depth. Much different than Depth 5 km Dip 40 C —

Dike displacement

Depth	Disp	Depth	Disp	Depth	Disp
4530	-.05	5000	-.225	5000	.3
4630	-.075	5020	-.350	5040	.325
4730	-.1	5060	-.375	5080	.35
4820	-.125	5160	-.4	5140	.375
4880	-.15	5280	-.425	5190	.4
4930	-.175	5380	-.45	5290	.425
4970	-.2	5400	-.475	5440	.45
		6500	-.482	6500	.482

fault

top x	Disp	bot x	Disp		
0	-.2	0	.3	440	.1
40	-.175	40	.275	500	.075
90	-.15	80	.25	520	.05
150	-.125	120	.225	540	.025
240	-.1	160	.2	560	0
300	-.075	220	.175		
400	-.05	300	.15		
500	-.025	360	.125		
560	0				

9/29/95 RWT

Setup Depth 5 km Dip 50 y

Same as 5-50 z except extended fault to 600 m

10/2/95

Depth 5 km Dip 50 y complete

Dike failed at 4091 m and propagated to depth 4474 m. Same start point as 50 z but did not propagate to fault.

?? Why does dike fail at 4000 m depth for all 5 km calc ??

Dike displacement

4360 — 0 →

Depth	Disp	Depth	Disp	Depth	Disp
4450	-.025	+5000	-.35	5000	.285
4500	-.05	5050	-.375	5030	.3
4600	-.075	5150	-.4	5060	.325
4670	-.1	5350	-.425	5120	.35
4740	-.125	6500	-.45	5180	.375
4800	-.15			5280	.4
4870	-.175			5400	.425
4930	-.2			6500	.44
4960	-.225				
5000	-.25				

10/2/95 RWT

Fault displacement

top x	Disp	bot x	Disp
0	-.225	0	.285
40	-.2	20	.275
80	-.175	40	.25
150	-.15	80	.225
200	-.125	120	.2
240	-.1	160	.175
300	-.075	220	.15
360	-.05	280	.125
420	-.025	340	.1
480	0	440	.075
540	+.025	540	.025
600	+.025	600	.025

10/5/95 [signature]

Report completed —

Project Complete

I HAVE REVIEWED THIS NOTEBOOK AND FIND IT IN GENERAL CONFORMANCE WITH QAP-001. A REVIEW OF THIS NOTE BOOK INDICATES THAT A SUITABLY TRAINED PERSON COULD DUPLICATE THE WORK DESCRIBED HERE.

H. Lawrence McKague

3/28/97

THIS BOOK IS TO BE ARCHIVED AS OF 6/23/98

H. Lawrence McKague

6/22/98