SCIENTIFIC NOTEBOOK
Development of the FAULTING Module

by

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1. INITIAL ENTRIES

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Project Title: Development of the FAULTING Module of Phase 3 IPA

Project Staff: Amitava Ghosh

By agreement with the CNWRA QA this NoteBook is to be printed at approximate quarterly intervals. This computerized Scientific NoteBook is intended to address the criteria of CNWRA QAP-001.

[Amitava Ghosh, February 28, 1996]

1.1 Objectives

The objective of this activity is to develop the FORTRAN coding of the faulting consequence (FAULTING) module for the Phase 3 of the Nuclear Regulatory Commission (NRC) Iterative Performance Assessment (IPA) activity. The basic approach to the FAULTING module has been described in Stirewalt et al. (1995). Taking into account the published data for faults at Yucca Mountain area, this module provides a framework for determining if the primary fault displacement (that is, displacement along the main fault trace rather than along associated secondary fractures) in the repository block could induce waste package disruption, the timing of that disruption, and the number of waste packages disrupted.
[Amitava Ghosh, February 28, 1996]

1.2 Technical Approaches

The codes for the FAULTING module will be written in Fortran 77. Fault displacement is generated in the FAULTING module along an assumed, unknown, and randomly located fault zone inside the simulation area. These unknown fault zones include those not distinguished or adequately characterized, as well as new faults which may develop during the 10,000 year regulatory time frame of interest. Strike direction is determined as either northeast or northwest observed in the field at and near Yucca Mountain. Whether the fault intersects the potential repository depends on location and orientation of the fault in the simulation area and total fault trace length. Whether waste packages are disrupted is dependent upon amount of displacement exceeding a threshold value which is governed by repository and waste package design and waste package emplacement geometry. If the threshold displacement is exceeded by either largest credible displacement in a single event or by smaller cumulative displacements with time through multiple events, then number and locations of waste packages intersected and disrupted can be calculated based on length of intersection of the fault zone with the repository, repository design, and waste package emplacement geometry. Location, trace orientation, geometry, activity, number and time and amount of largest credible displacement faulting events, and amount and time of cumulative displacements are chosen

randomly from range of published data represented as probability distribution functions (PDFs). It is assumed that the unknown fault zones can possess attributes similar to those of the Ghost Dance and Sundance faults. The fault zone is assigned a randomly selected width, and displacement in the zone is considered along both single and multiple slip surfaces. It is assumed that the variation in dip of the fault has little influence on number of waste packages disrupted, considering horizontal emplacement. If waste package disruption occurs as a result of either a largest credible displacement event or cumulative displacement, the timing of that disruption is relayed to the SOurce TErm Code (SOTEC) for calculation of radionuclide release.

The random numbers following a particular PDF will be generated primarily using the program LHS94 (version 1.1) (Iman and Shortencarier, 1984) which uses the Latin Hypercube method. However, using the LHS94 program is a two step process. All the random numbers needed to run the FAULTING modules should be known beforehand and need to generated in advance of running the module. The final version of the FAULTING module will have an user interface to do this. Additionally, each subroutine of the FAULTING module may use own random number generation routines during development. Currently, the LHS94 code is not under the code configuration management of CNWRA.

[Amitava Ghosh, February 28, 1996]

1.3 Computers, Computer Codes, and Data Files

Table 1-1. Computer, operating system, and compiler to be used in developing FAULTING module

Machine Name	Machine Type	Operating System	Compiler	Location
snowwhite	SUN SPARCstation 20	SUNOS 4.1	f77 (SUN)	Building 189

[Amitava Ghosh, February 28, 1996]

1.4 Mathematical Theory

Not Applicable

[Amitava Ghosh, February 28, 1996]

1.5 Assumptions

The assumptions for each of the parameters and the complete module are given in Stirewalt et al. (1995). [Amitava Ghosh, February 28, 1996]

1.6 Initial/Boundary Conditions

Not Applicable [Amitava Ghosh, February 28, 1996]

2. Development of the FAULTING Module

2.1 Mathematical Theory

2.1.1 Random Numbers Having Normal Distribution with Mean μ and Standard Deviation σ, N (μ, σ_2)

Random numbers have to be generated with mean μ and standard deviation σ so that there is 90 percent probability that the number will fall between A and B.

$$\mu = \frac{A+B}{2}$$

$$P(x \le A) = \frac{100-90}{2}\% = 5\% = 0.05$$

$$P(X \ge B) = 0.05$$

$$P(Z \le 1.645) = 0.05$$

For a standard normal variate Z,

$$P(Z \le 1.645) = 0.05$$

Standard deviation of the desired truncated normal distribution is $\sigma = \frac{X-\mu}{1.645} = \frac{B-\mu}{1.645} = \frac{B-A}{2.29}$

Generation of normally distributed random numbers is carried out following Ang and Tang (1984):

If U_1 and U_2 are two uncorrelated uniformly distributed random numbers between 0 and 1, then two normally distributed random numbers with mean μ and standard deviation σ are:

$$x_1 = \mu + \sigma \sqrt{-2 ln U_1}\, \cos 2\pi U_2$$

$$x_2 = \mu + \sigma \sqrt{-2 ln U_1}\, \sin 2\pi U_2$$

[Amitava Ghosh, March 31, 1996]

2.1.2 Beta Distribution in the Interval (A, B) with Parameters α and β

Random numbers Y from a general Beta distribution with lower and upper bounds A and B, respectively, may be obtained through

$$Y = \frac{X-A}{B-A}$$

where X is the corresponding random number for the standard Beta distribution

$$\mu_x = \frac{\alpha}{\alpha + \beta}$$

$$\sigma_x = \frac{\alpha \beta}{(\alpha+\beta)^2(\alpha+\beta+1)}$$

Therefore, $\mu_y = (B-A)\mu_x + A = \frac{A\beta + B\alpha}{\alpha + \beta}$

$$\sigma_y = (B-A)^2 \sigma_x = \frac{(B-A)^2 \alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}$$

Generation of Beta distributed random numbers is carried out following Ang and Tang (1984):

A random number X with pdf of the standard Beta distribution with shape parameters σ and β can be generated from

$$X = \frac{U_1^{1/\alpha}}{U_1^{1/\alpha} + u_2^{1/\beta}}$$

where U_1 and U_2 are two random numbers having the standard uniform distribution provided $U_1^{1/\alpha} + U_2^{1/\beta} \leq 1$.

[Amitava Ghosh, March 31, 1996]

2.1.3 Coordinates of the Point of Intersection of Two Straight Lines Defined by the Coordinates of the End Points

Line 1: End points are (x_1,y_1) and (x_2,y_2)
Line 1: End points are (x_3,y_3) and (x_4,y_4)
Intersection point: (x_i,y_i)

Equation of line 1:

$$\frac{Y-Y_1}{X-X_1} = \frac{Y_2-Y_1}{X_2-X_1} \qquad (1)$$

It goes through (x_i,y_i). Therefore,

$$\frac{Y_i-Y_1}{X_i-X_1} = \frac{Y_2-Y_1}{X_2-X_1} \qquad (2)$$

Similarly,

$$\frac{Y_i-Y_3}{X_i-X_3} = \frac{Y_4-Y_3}{X_4-X_3} \qquad (3)$$

Solving (2) and (3) for x_i and y_i, we get

$$x_i = \frac{(x_1-x_2)\,(x_3y_4-x_4y_3)+(x_3-x_4)\,(x_1y_2-x_2y_1)}{-(x_3y_1-x_4y_1-x_3y_2+x_4y_2-x_1y_3+x_2y_3+x_1y_4-x_2y_4)}$$

$$y_i = -\frac{x_2y_1y_3+x_4y_1y_3+x_1y_2y_3-x_4y_2y_3+x_2y_1y_4-x_3y_1y_4-x_1y_2y_4+x_3y_2y_4}{-x_3y_1+x_4y_1+x_3y_2-x_4y_2+x_1y_3-x_2y_3-x_1y_4+x_2y_4}$$

These solutions were also verified using the commercial program Mathematica. These equations were coded in the subroutine intersection.

These equations do not guarantee that the point of intersection of these lines are real, that is, the point lies on both the lines as shown:

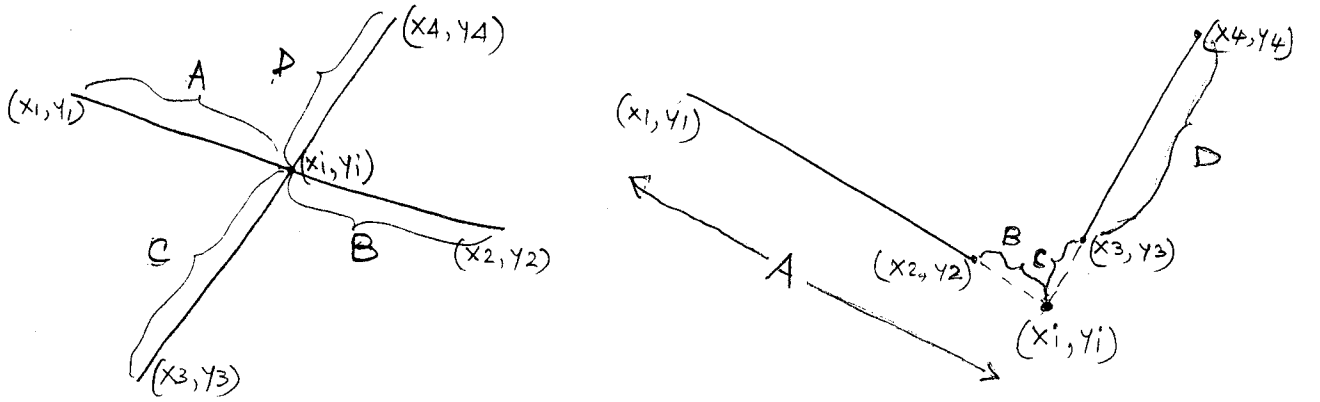

Figure 2-1. Determination of real intersection point of two finite straight lines

A = length of the line joining (x_1,y_1) and (x_i,y_i)
B = length of the line joining (x_2,y_2) and (x_i,y_i)
C = length of the line joining (x_3,y_3) and (x_i,y_i)
D = length of the line joining (x_4,y_4) and (x_i,y_i)
E = length of the line joining (x_1,y_1) and (x_2,y_2)
F = length of the line joining (x_3,y_3) and (x_4,y_4)

For the intersection to be real, either of the following two conditions needs to be tone.

$$A + B = E \Rightarrow (A + B) - E = 0$$

or,

$$C + D = F \Rightarrow (C + D) - F = 0$$

It should be recognized that comparison of real numbers having very similar magnitudes is problematic due to round off errors. Therefore, an acceptable tolerance should be used.

[Amitava Ghosh, March 31, 1996]

2.1.4 Determination whether a given point falls within a quadrilateral defined by the four corners.

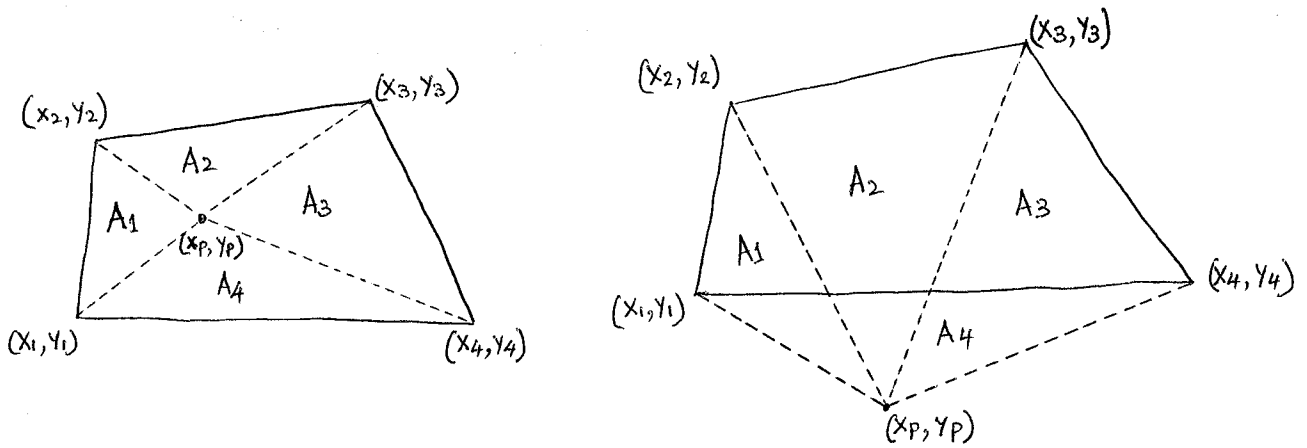

Figure 2-2. Determination whether a given point falls within a given quadrilateral

Given point is (x_p,y_p). The quadrilateral has corners defined by (x_1,y_1), (x_2,y_2), (x_3,y_3), and (x_4,y_4).

A1: area of triangle (x_1,y_1), (x_2,y_2), (x_p,y_p)
A2: area of triangle (x_2,y_2), (x_3,y_3), (x_p,y_p)
A3: area of triangle (x_3,y_3), (x_4,y_4), (x_p,y_p)
A4: area of triangle (x_4,y_4), (x_1,y_1), (x_p,y_p)

Area of quadrilateral (x_1,y_1), (x_2,y_2), (x_3,y_3), (x_4,y_4) = A
= area of [triangle (x_1,y_1), $x_2,y_2)$, (x_3,y_3) + triangle (x_3,y_3), (x_4,y_4) (x_1,y_1)]

If the point (x_p,y_p) is inside the quadrilateral, then

$$A = A_1 + A_2 + A_3 + A_4$$

If outside,

$$A < (A_1 + A_2 + A_3 + A_4)$$

[Amitava Ghosh, March 31, 1996]

2.1.5 Determination of the Fault Length Intersected by the Repository Block

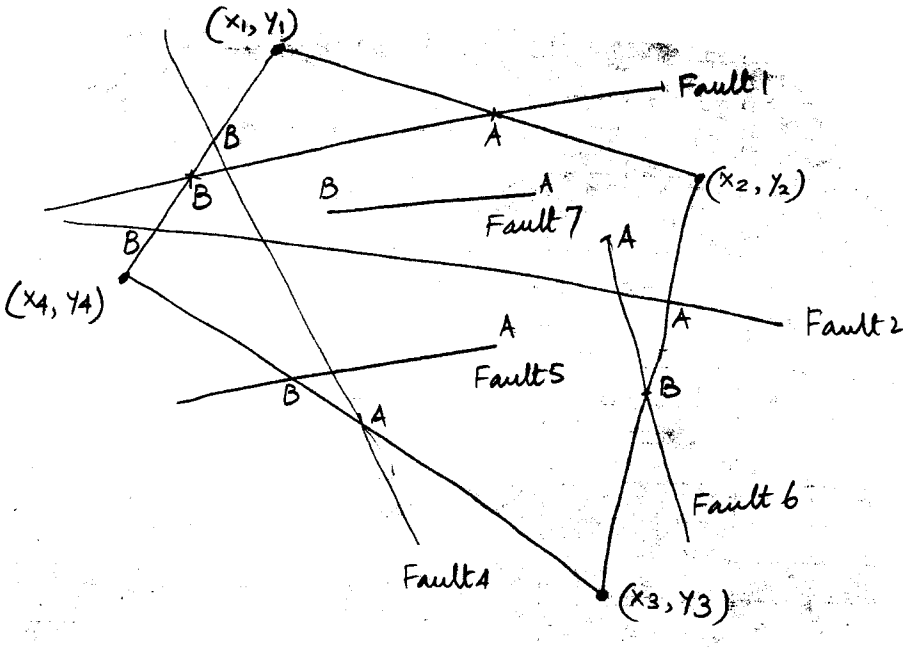

Figure 2-3. Determination of the length of a given fault intersected by a repository block

- Fault 7: Intersection length = Fault length
- Fault 5, Fault 6: Intersection length = AB: need to find only B
- Fault 1, Fault 2, Fault 3, Fault 4: Intersection Length = AB: need to know both A and B

Known: (i) Two ends of each fault (xf_1,yf_1) and (xf_2, yf_2)
(ii) Four corners (x_1,y_1), (x_2,y_2), (x_3,y_3), (x_4,y_4)

Step 1: Determine whether each end of the fault is within the boundary
if yes, intersection length = fault length

Step 2: If one end is within the boundary, determine
(i) which segment it is intersecting
(ii) calculate length AB

Step 3: If both ends are outside the boundary, determine
(i) which segments it is intersecting
(ii) calculate length AB

[Amitava Ghosh, March 31, 1996]

2.2 Input Data

The FAULTING module requires information about the origin of the simulation area and the boundaries of different repository blocks which are given in terms of the coordinates of the four corners.

The origin of the simulation area was taken as 170500 m East and 233000 m North, which falls in the middle of the primary emplacement area. Different emplacement areas are given by (TRW Environmental Safety Systems Inc., 1994):

Region Primary Upper:
[(170500E, 234800N), (171300E, 234500N), (171100E, 231100N), (169800N, 231500E)]

Region Primary Lower:
[(171600E, 233700N), (172300E, 233300N), (171700E, 232000N), (171500E, 232100N)]

Optional Region A:
[(170800E, 236300N), (171300E, 236400N), (171950E, 235500N), (171300E, 235200N)]

Optional Region B:
[(169000E, 236800N), (169700E, 236500N), (169400E, 234500N), (168500E, 234800N)]

Optional Region C:
[(168300E, 234500N), (168900E, 234200N), (168200E, 232200N), (167600E, 232500N)]

Optional Region D:
[(169200E, 234200N), (169700E, 234000N), (169100E, 231500N), (168200E, 231700N)]

[Amitava Ghosh, March 31, 1996]

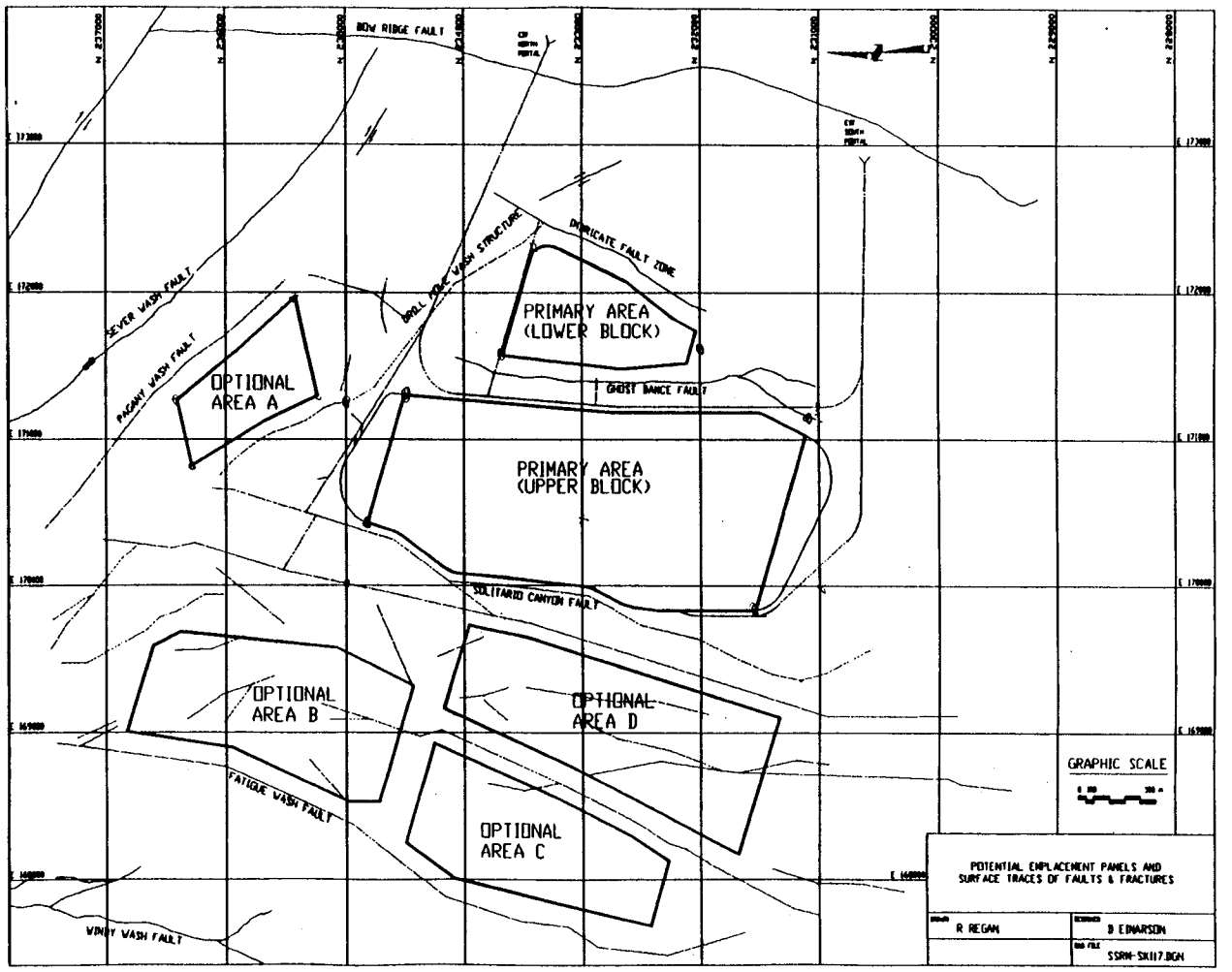

Figure 2-4. Different repository blocks (TRW Environmental Safety Systems Inc., 1995)

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Iman, R.L., and M.J. Shortencarier. 1984. *A FORTRAN 77 Program and User's Guide for the Generation of Latin Hypercube and Random Samples for Use With Computer Models*. SAND83-2365 and NUREG/CR-3624. Albuquerque, NM: Sandia National Laboratories.

Stirewalt, G.L., S.M. McDuffie, R.D. Manteufel, and R.W. Janetzke. 1995. *Technical Specifications for a Fault Displacement Module*. Report to Nuclear Regulatory Commission. San Antonio, TX: Center for Nuclear Waste Regulatory Analyses.

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CENTER FOR NUCLEAR WASTE REGULATORY ANALYSES

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[Amitava Ghosh, February 28, 1996]

The code in the present form has own subroutines to generate necessary random numbers from a given distribution. Therefore, at this point, there is no need to generate the random numbers using the LHS routines before the run and use them while running this module. At present, this is quite a cumbersome process as we have to estimate beforehand how many random numbers from each specific distribution is needed. It may also be extremely difficult to guess beforehand as the number of random numbers needed for any simulation drastically goes down if the generated fault does not intersect the given repository region.

[Amitava Ghosh, June 27, 1996]

It was also decided to carry out the complete calculation in double precision. The reason is as follows. In the calculation done by this module, we are dealing with very large numbers (coordinates of the faults) and very small numbers (slipping rate on a fault surface). In both cases, it becomes necessary to keep enough precision in the calculations (at least more than 6 significant digits) so that rounding off error does not mislead the calculation sequence.

[Amitava Ghosh, June 27, 1996]

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$$y_i=-\frac{x_2y_1y_3+x_4y_1y_3+x_1y_2y_3-x_4y_2y_3+x_2y_1y_4-x_3y_1y_4-x_1y_2y_4+x_3y_2y_4}{-x_3y_1+x_4y_1+x_3y_2-x_4y_2+x_1y_3-x_2y_3-x_1y_4+x_2y_4}$$

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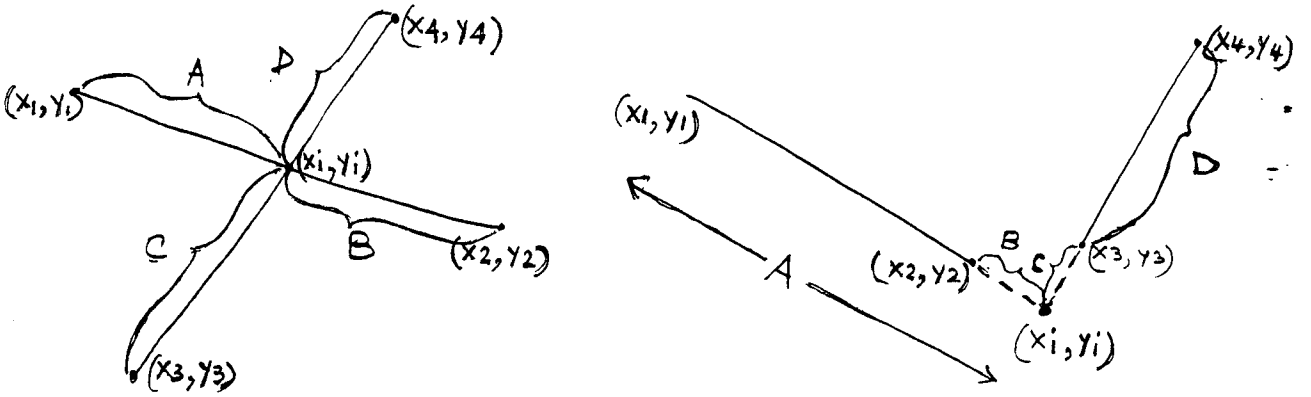

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B = length of the line joining (x_2,y_2) and (x_i,y_i)
C = length of the line joining (x_3,y_3) and (x_i,y_i)
D = length of the line joining (x_4,y_4) and (x_i,y_i)
E = length of the line joining (x_1,y_1) and (x_2,y_2)
F = length of the line joining (x_3,y_3) and (x_4,y_4)

For the intersection to be real, either of the following two conditions needs to be true.

$$A + B = E \rightarrow (A + B) - E = 0$$

or,

A = length of the line joining (x_1,y_1) and (x_i,y_i)
B = length of the line joining (x_2,y_2) and (x_i,y_i)
C = length of the line joining (x_3,y_3) and (x_i,y_i)
D = length of the line joining (x_4,y_4) and (x_i,y_i)
E = length of the line joining (x_1,y_1) and (x_2,y_2)
F = length of the line joining (x_3,y_3) and (x_4,y_4)

For the intersection to be real, either of the following two conditions needs to be true.

$$A + B = E \Rightarrow (A + B) - E = 0$$

or,

$$C + D = F \Rightarrow (C + D) - F = 0$$

It should be recognized that comparison of real numbers having very similar magnitudes is problematic due to round off errors. Therefore, an acceptable tolerance should be used.

[Amitava Ghosh, March 31, 1996]

The formula for x_i has been changed to be parallel with that of y_i so that the coding of the subroutine becomes easier. The revised formula is as follows:

$$x_i = \frac{-x_2x_4y_3+x_1x_4y_3+x_2x_4y_1-x_2x_3y_1-x_1x_4y_2+x_1x_3y_2+x_2x_3y_4-x_1x_3y_4}{-x_3y_1+x_4y_1+x_3y_2-x_4y_2+x_1y_3-x_2y_3-x_1y_4+x_2y_4}$$

For the intersection to be real, both of the above two conditions needs to be true. Otherwise, in some cases wrong conclusions will be made. This has been corrected in the code.

[Amitava Ghosh, May 23, 1996]

2.1.2. Determination whether a given point falls within a quadrilateral defined by the four corners

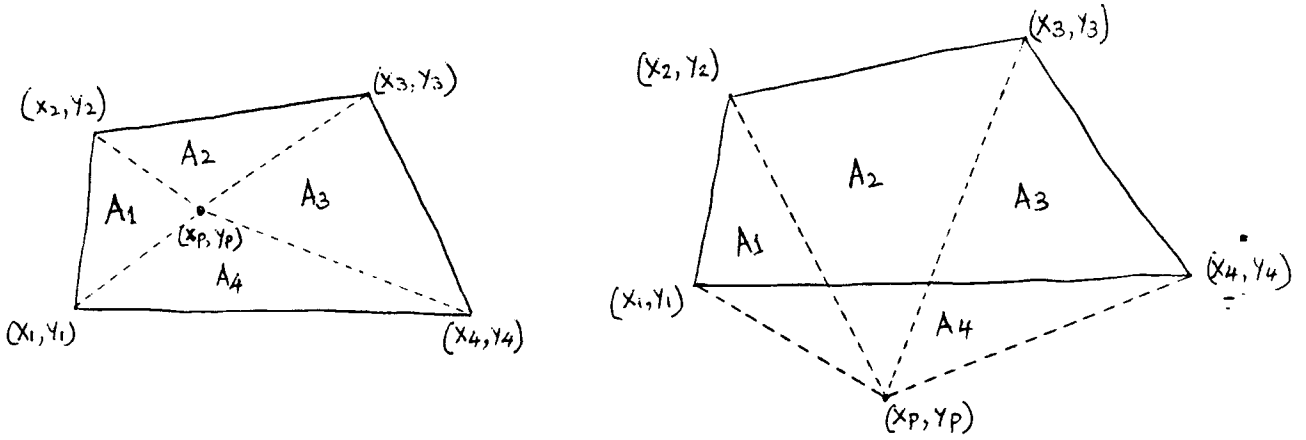


Figure 2-2. Determination whether a given point falls within a given quadrilateral

Given point is (x_p,y_p). The quadrilateral has corners defined by $(x_1,y_{1)}$, (x_2,y_2), (x_3,y_3), and (x_4,y_4).

A1: area of triangle (x_1,y_1), (x_2,y_2), (x_p,y_p)
A2: area of triangle (x_2,y_2), (x_3,y_3), (x_p,y_p)
A3: area of triangle (x_3,y_3), (x_4,y_4), (x_p,y_p)
A4: area of triangle (x_4,y_4), (x_1,y_1), (x_p,y_p)

Area of quadrilateral (x_1,y_1), (x_2,y_2), (x_3,y_3), (x_4,y_4) = A
= area of [triangle (x_1,y_1), $x_2,y_2)$, (x_3,y_3) + triangle (x_3,y_3), (x_4,y_4) (x_1,y_1)]

If the point (x_p,y_p) is inside the quadrilateral, then

$$A = A_1 + A_2 + A_3 + A_4$$

If outside,

$$A < (A_1 + A_2 + A_3 + A_4)$$

[Amitava Ghosh, March 31, 1996]

2.1.3. Determination of the Fault Length Intersected by the Repository Block

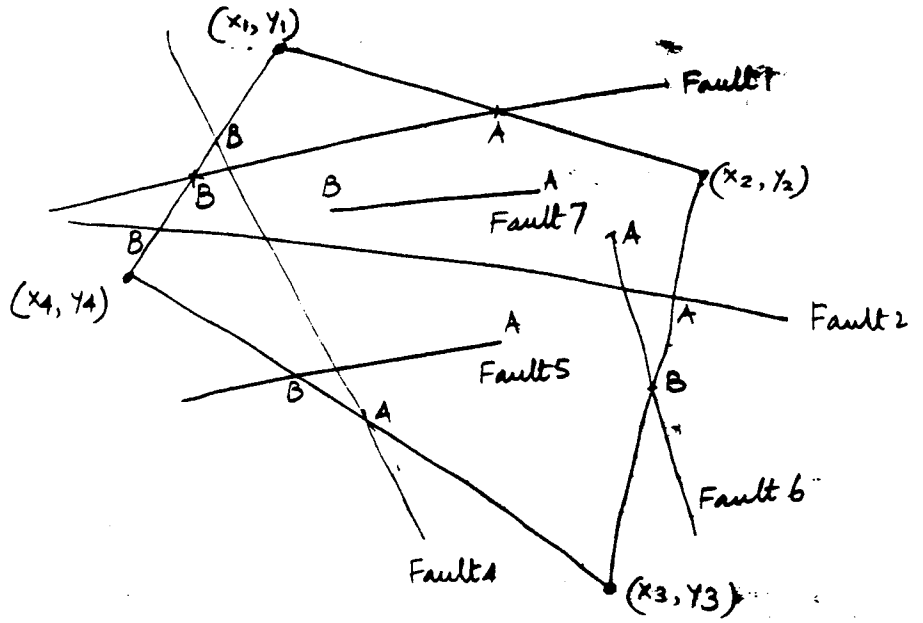


Figure 2-3. Determination of the length of a given fault intersected by a repository block

- Fault 7: Intersection length = Fault length
- Fault 5, Fault 6: Intersection length = AB: need to find only B
- Fault 1, Fault 2, Fault 3, Fault 4: Intersection Length = AB: need to know both A and B

Known: (i) Two ends of each fault (xf_1,yf_1) and (xf_2, yf_2)
(ii) Four corners (x_1,y_1), (x_2,y_2), (x_3,y_3), (x_4,y_4)

Step 1: Determine whether each end of the fault is within the boundary
if yes, intersection length = fault length

Step 2: If one end is within the boundary, determine
(i) which segment it is intersecting
(ii) calculate length AB

Step 3: If both ends are outside the boundary, determine

(i) which segments it is intersecting
(ii) calculate length AB

[Amitava Ghosh, March 31, 1996]

The length of the portion of a randomly generated fault intersected by a given repository region is calculated following the above-mentioned algorithm. Subroutine *checkin* is used to determine whether both ends of the fault fall within the given region. If both ends of the fault are within the given region then the intersected length is the length of the fault. If one end or both ends fall outside the given region, then subroutine *inlength* is called to determine first the intersection point(s) of the fault and the sides of the quadrilateral region. There will be one or two real intersection points depending on whether one or two end points fall outside the region, respectively. The intersected length for the first case is the distance between the real intersection point and the other end point of the fault which falls within the region. The intersected length for the second case is the distance between the two intersection points.

[Amitava Ghosh, June 7, 1996]

2.1.4. Random Numbers Having Normal Distribution with Mean μ and Standard Deviation σ, N (μ, σ_2)

Random numbers have to be generated with mean μ and standard deviation σ so that there is 90 percent probability that the number will fall between A and B.

$$\mu = \frac{A+B}{2}$$

$$P(x \le A) = \frac{100-90}{2}\% = 5\% = 0.05$$

$$P(X \ge B) = 0.05$$

$$P(Z \le 1.645) = 0.05$$

For a standard normal variate Z,

$$P(Z \le 1.645) = 0.05$$

Standard deviation of the desired truncated normal distribution is $\sigma = \frac{X-\mu}{1.645} = \frac{B-\mu}{1.645} = \frac{B-A}{2.29}$

Generation of normally distributed random numbers is carried out following Ang and Tang (1984):

If U_1 and U_2 are two uncorrelated uniformly distributed random numbers between 0 and 1, then two normally distributed random numbers with mean μ and standard deviation σ are:

$$x_1 = \mu + \sigma\sqrt{-2lnU_1}\,\mathrm{Cos}2\pi U_2$$
$$x_2 = \mu + \sigma\sqrt{-2lnU_1}\,\mathrm{Sin}2\pi U_2$$

[Amitava Ghosh, March 31, 1996]

Standard deviation of the desired truncated normal distribution is $\sigma = \frac{X-\mu}{1.645} = \frac{B-\mu}{1.645} = \frac{B-A}{3.29}$

This is the corrected form of the equation as 2x1.645 is equal to 3.29, not 2.29 as typed.

[Amitava Ghosh, May 21, 1996]

2.1.5. Beta Distribution in the Interval (A, B) with Parameters α and β

Random numbers Y from a general Beta distribution with lower and upper bounds A and B, respectively, may be obtained through

$$Y = \frac{X-A}{B-A}$$

where X is the corresponding random number for the standard Beta distribution

$$\mu_x = \frac{\alpha}{\alpha+\beta}$$
$$\sigma_x = \frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}$$

Therefore, $\mu_y = (B-A)\mu_x + A = \frac{A\beta + B\alpha}{\alpha+\beta}$

$$\sigma_y = (B-A)^2\sigma_x = \frac{(B-A)^2\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}$$

Generation of Beta distributed random numbers is carried out following Ang and Tang (1984):

A random number X with pdf of the standard Beta distribution with shape parameters σ and β can be generated from

$$X=\frac{U_1^{1/\alpha}}{U_1^{1/\alpha}+u_2^{1/\beta}}$$

where U_1 and U_2 are two random numbers having the standard uniform distribution provided $U_1^{1/\alpha}+U_2^{1/\beta}\le 1$.

[Amitava Ghosh, March 31, 1996]

2.1.6. LogBeta Distribution in the Interval (A, B) with Parameters α and β

X is standard beta distributed with mean equal to 0 and standard deviation equal to 1. Then Y has logbeta distribution if

$$Y = e^X$$

which means

$$\ln Y = X$$

has beta distribution. Consequently, the lower and upper limits will be:

$$a^* = \ln a$$

$$b^* = \ln b$$

Now, we have to generate a standard beta distribution with lower and upper limits are a^* and b^* respectively.

Mean of logbeta distribution $\mu = e^{\frac{\alpha}{\alpha+\beta}}$

Variance of logbeta distribution $\alpha = e^{\frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}}$

Given $\alpha = 1.5, \quad \beta = 3.0$

$$\mu = e^{\frac{1.5}{4.5}} = 1.3956$$

$$\sigma = e^{\frac{1.5x3}{4.5^2x(5.5)}} = 1.0412$$

Minimum value $= e^0 = 1$

Maximum value $= e^1 = 2.71828$

Therefore, standard Beta x, i.e., within interval (0,1) distribution, when converted to logbeta distribution Y, will be within the interval (1, 2.71828)

$$Y = \frac{x-a}{b-a} = \frac{x-1}{1.71828}$$

Y will be logbeta distributed with interval between (0,1)

If, for example, we want random numbers which is logbeta within interval (A,B), then:

$$Z = Y(B-A)+A$$

$$Z = \frac{x-a}{b-a}\cdot(B-A)+A$$

$$= \frac{(x-a)(B-A)+A(b-A)}{b-a} = \frac{x(B-A)}{b-a} - \frac{a(B-A)}{b-a} + A$$

$$= x\frac{B-A}{b-a} + \frac{-aB+aA+bA-aA}{b-a}$$

$$= x\frac{B-A}{b-a} + \frac{bA-aB}{b-a}$$

[Amitava Ghosh, June 7, 1996]

2.1.7. Representation of Dip Angle

The given definition of dip given in Stirewalt et al. (1995) is quite inconvenient for computer processing. Dip direction and dip angle would have been a better alternative way of expressing the orientation of fault planes. Unfortunately, the data given here do not have correspondence between the strike and dip of a given fault plane. The field observation is restricted to the distribution of fault dip in two dominant fault orientations, namely, northwest (NW) and northeast (NE). For example, a dip of 60W does not belong to the plane with a particular fault with a given strike. Rather the data give the distribution of strike and dip independently.

A scheme has been devised here to express dip without any other information of direction, e.g., NW, NE, or W. As the faults are striking NE or NW, they will dip either to east or west. Therefore, in this scheme, the dip angle is always measured from the East direction. In other words, dip angle 0 degree and dipping towards east is dip 0. Similarly, dip angle 0 degree and dipping towards west is dip 180 degree. A dip angle of 30 degree and dipping east is dip 30 and dipping west is dip 120 degree.

It should be noted here that this scheme is not quite general and will not work if a fault has the strike towards east. In Yucca Mountain region, the fault orientation is either NE or NW. Therefore, this scheme will work without any problem. A better scheme is necessary to make this code more general and applicable to any other region.

[Amitava Ghosh, June 7, 1996]

2.2. Input Data

2.2.1. Simulation and Repository Regions

The FAULTING module requires information about the origin of the simulation area and the boundaries of different repository blocks which are given in terms of the coordinates of the four corners.

The origin of the simulation area was taken as 170500 m East and 233000 m North, which falls in the middle of the primary emplacement area. Different emplacement areas are given by (TRW Environmental Safety Systems Inc., 1995):

Region Primary Upper:
[(170500E, 234800N), (171300E, 234500N), (171100E, 231100N), (169800N, 231500E)]

Region Primary Lower:
[(171600E, 233700N), (172300E, 233300N), (171700E, 232000N), (171500E, 232100N)]

Optional Region A:

[(170800E, 236300N), (171300E, 236400N), (171950E, 235500N), (171300E, 235200N)]

Optional Region B:
[(169000E, 236800N), (169700E, 236500N), (169400E, 234500N), (168500E, 234800N)]

Optional Region C:
[(168300E, 234500N), (168900E, 234200N), (168200E, 232200N), (167600E, 232500N)]

Optional Region D:
[(169200E, 234200N), (169700E, 234000N), (169100E, 231500N), (168200E, 231700N)]

[Amitava Ghosh, March 31, 1996]

Figure 2-4 is from TRW Environmental Safety Systems Inc. (1995) showing the emplacement regions. Figure 2-5 shows the plots of the regions given by the above-listed coordinate points.

[Amitava Ghosh, June 7, 1996]

2.2.2. Development of Parameter File *fault.inc*

This code requires many site-specific values for different parameters. Previously, the values of these parameters were defined inside the code at the appropriate places where they were first defined. This may be helpful to read the code but has potential danger of accidentally modifying the parameters values during some modification of the code. Consequently, all these constants are declared in a separate file called *fault.inc* which is included in this code at the beginning of compilation. Any modification to the parameters can be done independently in the file *fault.inc* without any possibility of modifying any part of the code accidently. The content of the file *fault.inc* is given below:

```
c
c....C**************************************************************
c     This file contains values of different variables used in the
c     FAULTING module. Any change to the data should be done here
c     so that the program remains unaffected.
c....C**************************************************************
c


c
c... Coordinates of the square region (meter)
c
c
c     Define the coordinates of the square region
```

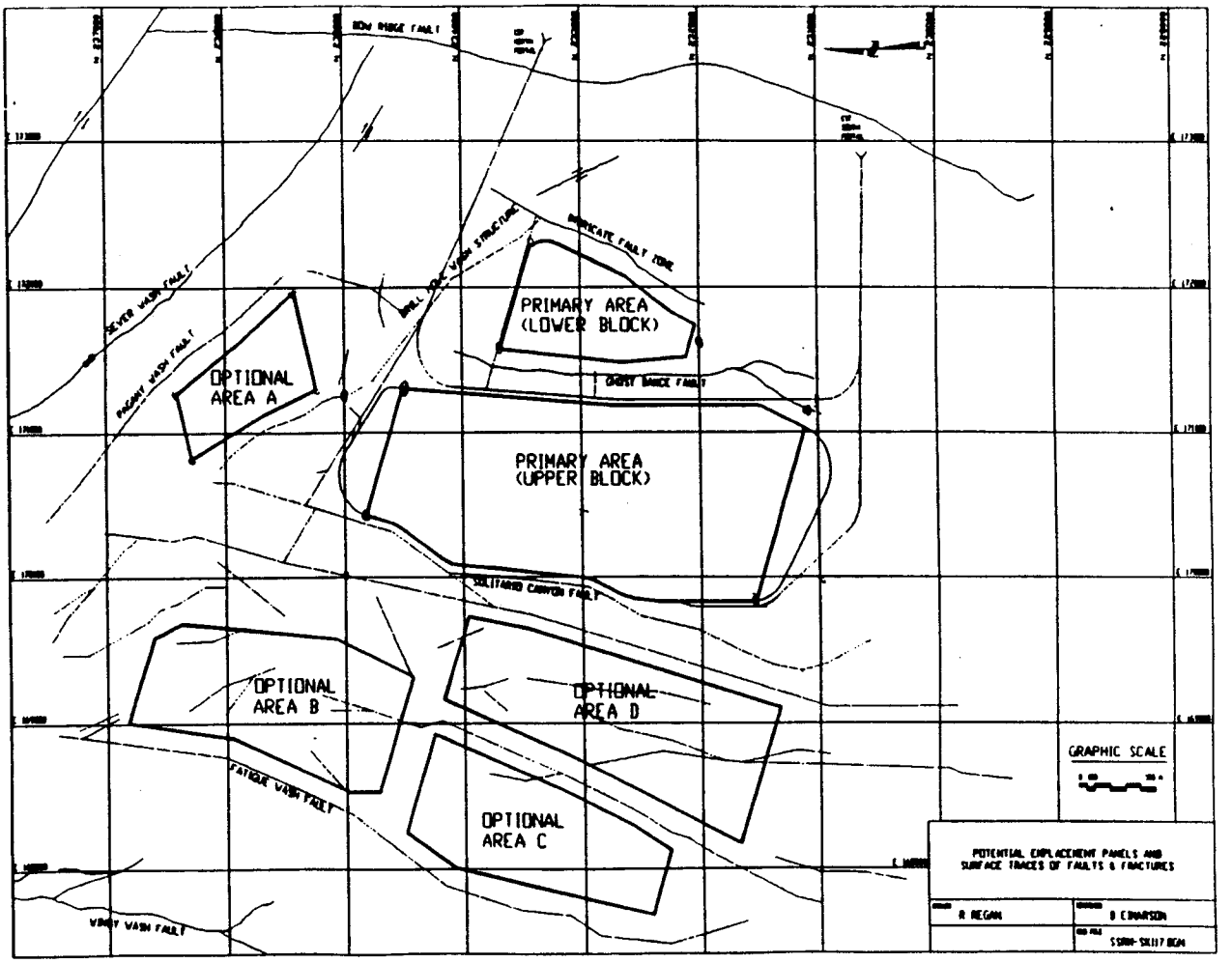


Figure 2-4 Different repository blocks (TRW Environmental Safety Systems Inc., 1995)

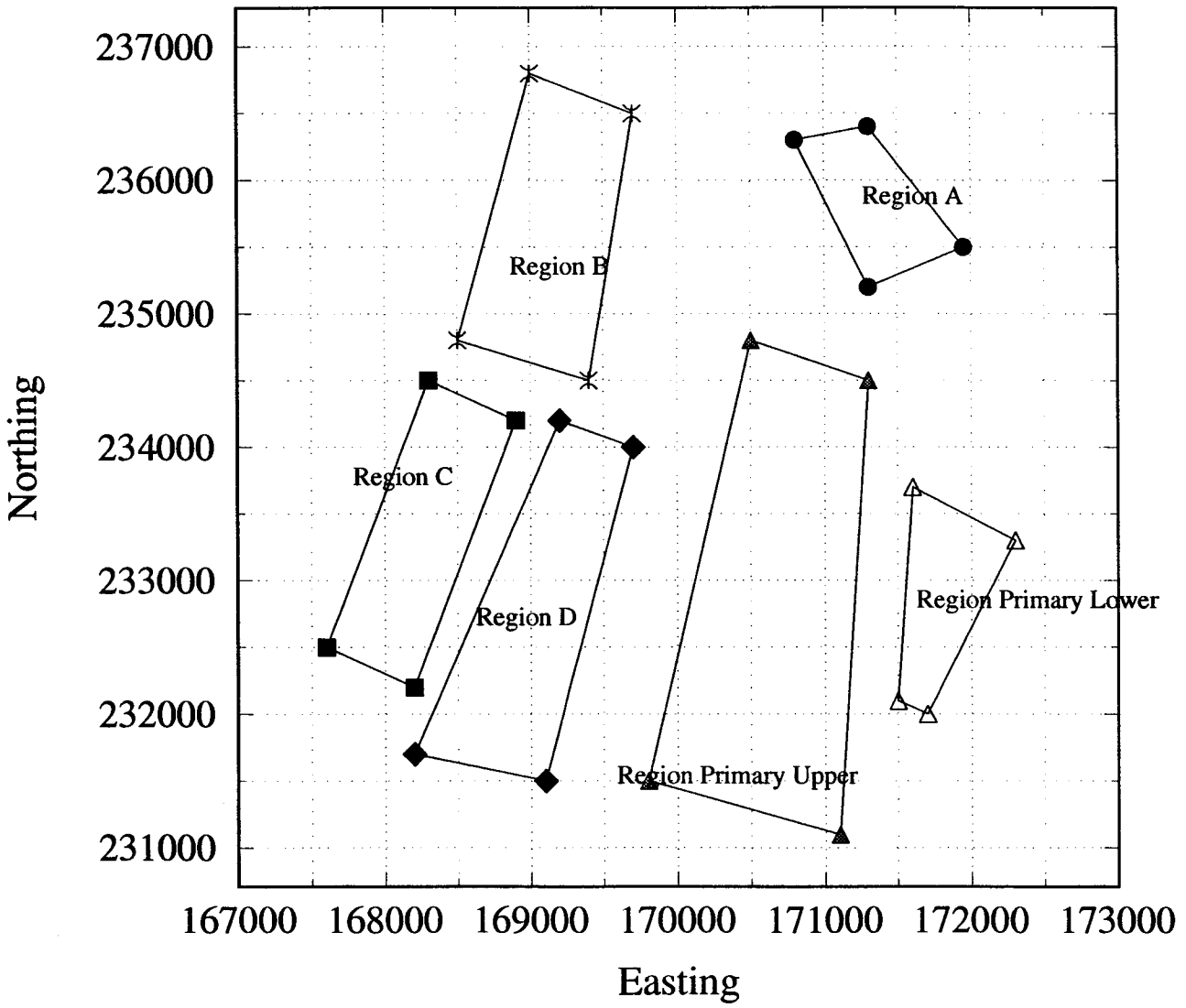


Figure 2-5 Different repository blocks as modeled in the FAULTING module

```
c     Origin is defined in the middle of the Primary Area (Upper Block)
c     x0 = 170500 East = 170500m, y0 = 233000 North = 233000 m
c     The simulation block is 50km x 50 km centered at (x0,y0)
c

      xleft   = 145500.0
      xright  = 195500.0
      ybottom = 208000.0
      ytop    = 258000.0

c
c...  Probability of fault zone orientation
c

      pforient = 0.25

c
c...  Strike of fault zone (degree, measured from North)
c

      min_SNW = 115.0d0
      max_SNW = 130.0d0

      min_SNE = 65.0d0
      max_SNE = 95.0d0

c
c...  Total trace length (meter)
c

      min_ltNW = 2000.0d0
      max_ltNW = 10000.0d0

      min_ltNE = 3000.0d0
      max_ltNE = 12000.0d0

c
c...  Dip angle (degree, measured from East)
c

      min_thetaNW = 80.0d0
      max_thetaNW = 100.0d0
```

```
      min_thetaNE = 90.0d0
      max_thetaNE = 120.0d0

c
c...  Fault Width (meter)
c

      min_wNW = 0.5d0
      max_wNW = 275.0d0

      min_wNE = 0.5d0
      max_wNE = 365.0d0

      alpha = 1.5d0
      beta = 3.0d0

c
c...  Time of coourance of largest credible displacement faulting event (year)
c

      min_t1 = 0.0d0
      max_t1 = 10000.0d0

c
c...  Amount of largest credible displacement per faulting event (meter)
c

      min_LDNW = 4.5d-2
      max_LDNW = 25.0d-2

      min_LDNE = 6.0d-2
      max_LDNE = 45.0d-2

c
c...  Largest credible displacement along multiple slip surfaces (meter)
c

      LD_max = 45.0d-2

c
c...  Amount of cumulative displacement rate (meter/year)
c
```

```
      min_CDNW = 0.0d-3
      max_CDNW = 0.01d-3

      min_CDNE = 0.00004d-3
      max_CDNE = 0.007d-3

c
c...  Threshold Displacement (meter)
c

      min_TD = 0.1d0
      max_TD = 0.5d0
```

[Amitava Ghosh, June 7, 1996]

3. VERIFICATION OF DIFFERENT PARTS OF THE FAULTING MODULE

3.1. Calculation of Intersected Length of a Fault

In this case, the coordinates of two ends of four faults were tested. The faults are shown in Figure 3-1. Four faults were tested: Fault 1 and Fault 2 fall completely within the repository region, in this case Region A. One end of Fault 3 intersects the region (only one end inside the region). Both ends of Fault 4 are outside the region, as shown in Figure 3-1. The coordinates of the both ends of the faults are given below along with the fault length and the length of the fault intersected by the repository region A.

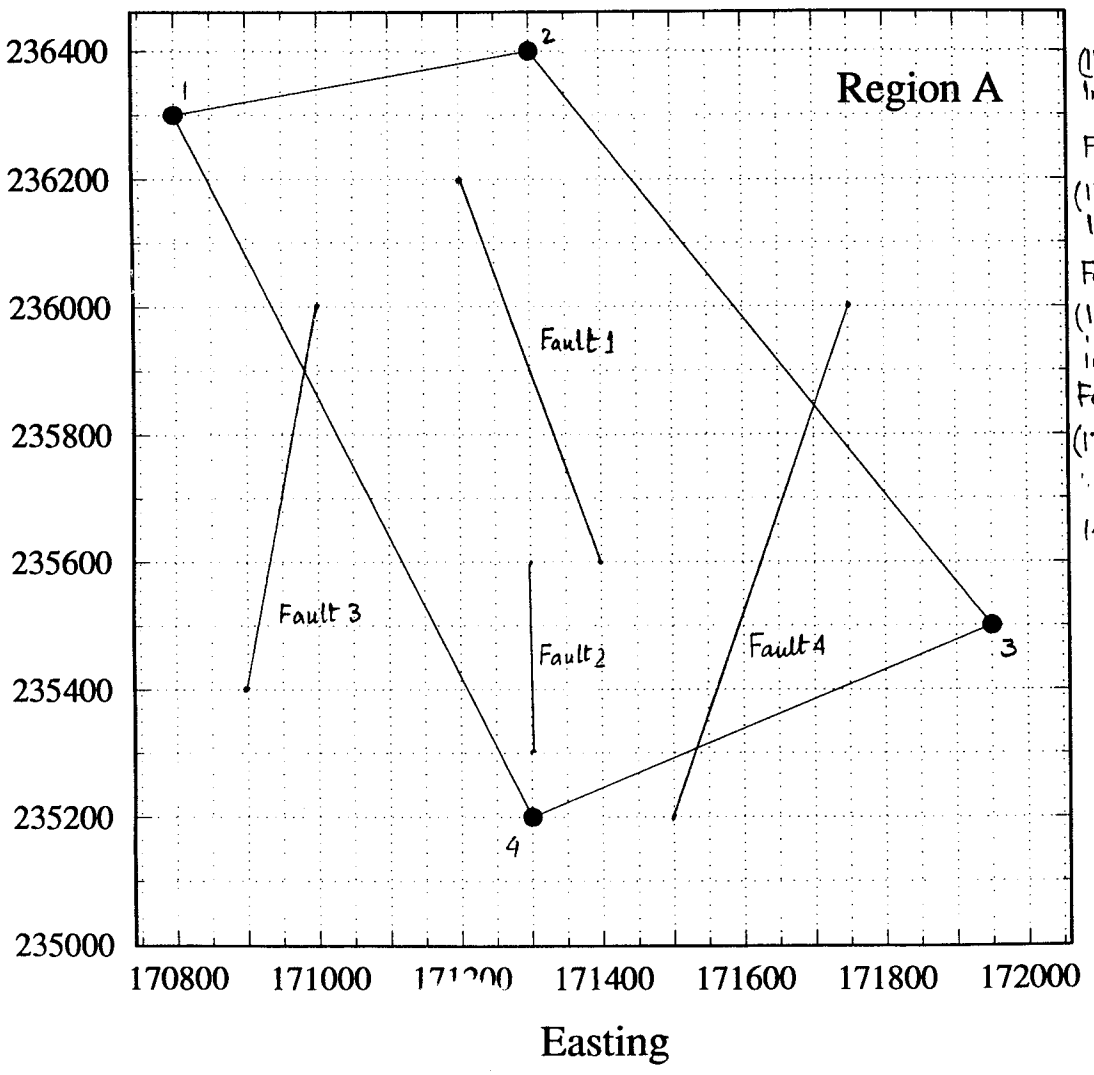
Fault 1:
End 1: [171200, 236200] End 2: [171400, 235600]
Length = 632.456
Intersected Length = 632.456

Fault 2:
End 1: [171300, 235600] End 2: [171300, 235300]
Length = 300.000
Intersected Length = 300.000

Fault 3:
End 1: [170900, 235400] End 2: [171000, 236000]
Length = 608.276
Intersected Length = 103.852

Fault 4:
End 1: [171500, 235200] End 2: [171750, 236000]
Length = 838.153
Intersected Length = 562.013

Figures 3-2 and 3-3 show Fault 3 and Fault 4 and the segments of the region intersected (real intersection) by them. Following are the results from the FAULTING module which shows good agreements with the results.



Fault 1:
(171200, 236200) & (171400, 235600)
Intersected Length = 632.456

Fault 2:
(171300, 235600) & (171300, 235300)
Intersected Length = 300.000 ✓

Fault 3:
(170900.235400) & (171000, 236000)
Length = 608.276 ✓
Intersected Length = 103.8520

Fault 4:
(171500, 235200) & (171750, 236000)
Length = 838.153 ✓
Intersected Length = 562.013

Figure 3-1 Region A with four fault planes used in verification of the code

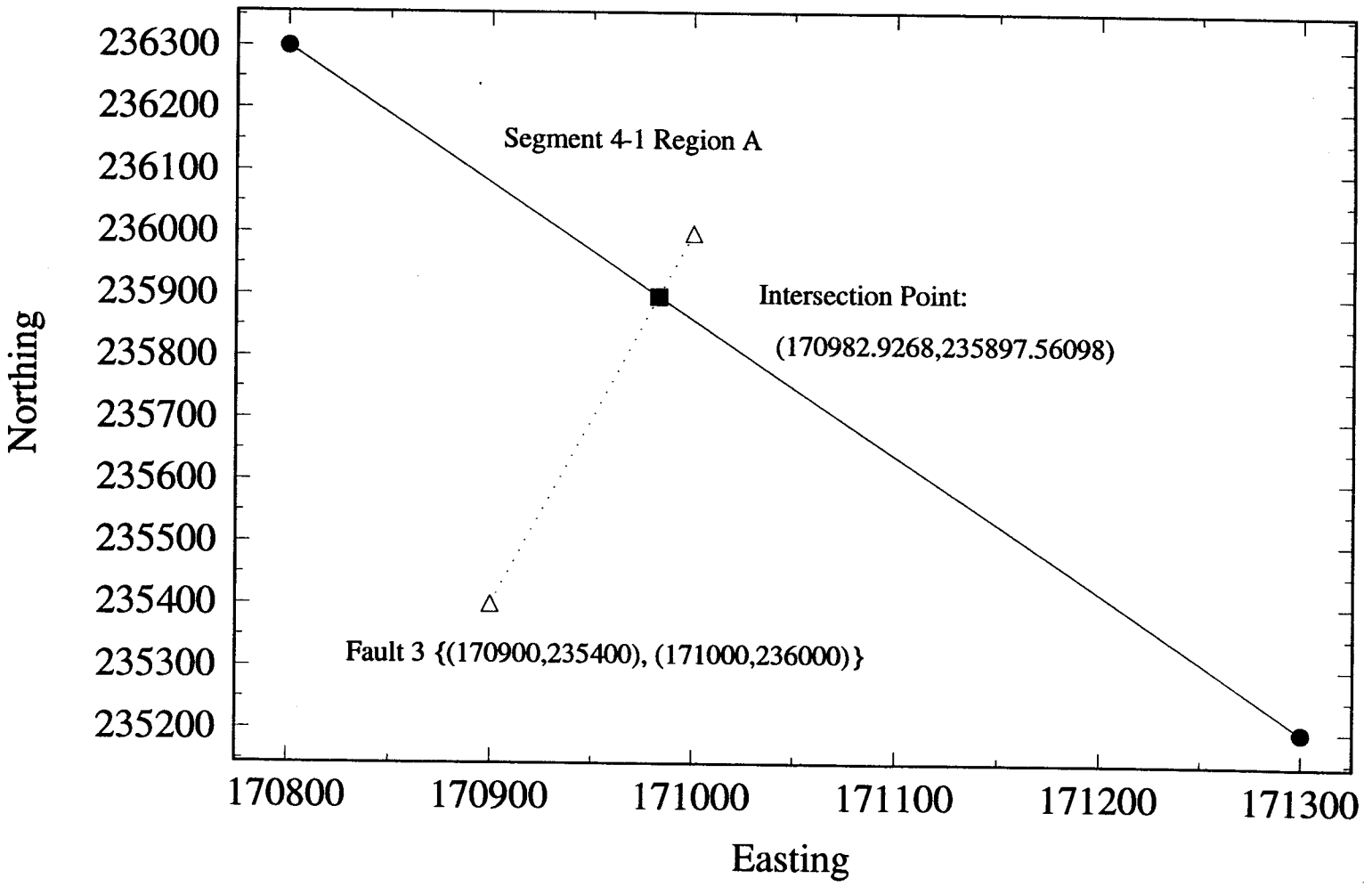


Figure 3-2 Intersection point of Fault 3 and segments of Region A

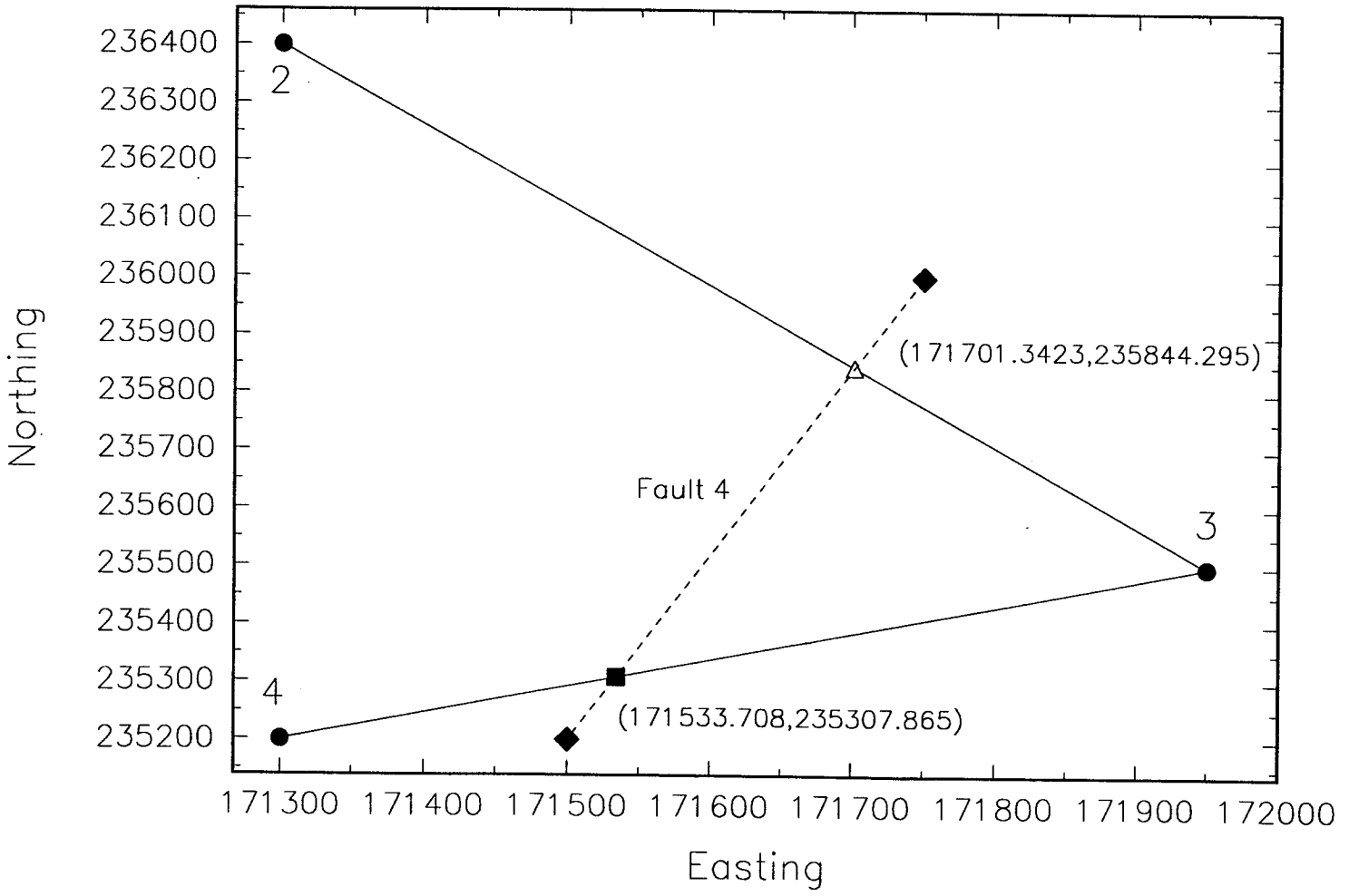


Figure 3-3 Intersection points of Fault 4 and segments of Region A

FAULT 1:

x1 of fault => 171200
y1 of fault => 236200
x2 of fault => 171400
y2 of fault => 235600
Region (PU,PL,A,B,C,D) => A

... Fault Plane ...
End 1: x = 171200.00000000 y = 236200.00000000
End 2: x = 171400.00000000 y = 235600.00000000
Region: A

x(1) = 170800.0 y(1) = 236300.0
x(2) = 171300.0 y(2) = 236400.0
x(3) = 171950.0 y(3) = 235500.0
x(4) = 171300.0 y(4) = 235200.0
x(5) = 170800.0 y(5) = 236300.0

171200.00000000 236200.00000000 falls inside the region
171400.00000000 235600.00000000 falls inside the region

Intersection Points:
Point 1: 171200.00000000 236200.00000000
Point 2: 171400.00000000 235600.00000000
Intersected length = 632.45553203368

Another run => y

FAULT 2:

x1 of fault => 171300
y1 of fault => 235600
x2 of fault => 171300
y2 of fault => 235300
Region (PU,PL,A,B,C,D) => A

... Fault Plane ...
End 1: x = 171300.00000000 y = 235600.00000000
End 2: x = 171300.00000000 y = 235300.00000000
Region: A

x(1) = 170800.0 y(1) = 236300.0
x(2) = 171300.0 y(2) = 236400.0
x(3) = 171950.0 y(3) = 235500.0
x(4) = 171300.0 y(4) = 235200.0
x(5) = 170800.0 y(5) = 236300.0

171300.00000000 235600.00000000 falls inside the region
171300.00000000 235300.00000000 falls inside the region

Intersection Points:
Point 1: 171300.00000000 235600.00000000
Point 2: 171300.00000000 235300.00000000
Intersected length = 300.00000000000

Another run => y

FAULT 3:

x1 of fault => 170900
y1 of fault => 235400
x2 of fault => 171000
y2 of fault => 236000
Region (PU,PL,A,B,C,D) => A

... Fault Plane ...
End 1: x = 170900.00000000 y = 235400.00000000
End 2: x = 171000.00000000 y = 236000.00000000
Region: A

x(1) = 170800.0 y(1) = 236300.0
x(2) = 171300.0 y(2) = 236400.0
x(3) = 171950.0 y(3) = 235500.0
x(4) = 171300.0 y(4) = 235200.0
x(5) = 170800.0 y(5) = 236300.0

170900.00000000 235400.00000000 falls outside the region
171000.00000000 236000.00000000 falls inside the region

In subroutine Intersection
x1 = 170800.00000000 y1 = 236300.00000000
x2 = 171300.00000000 y2 = 236400.00000000
x3 = 170900.00000000 y3 = 235400.00000000

x4 = 171000.00000000 y4 = 236000.00000000
Part 1 = -16078881000000. Part 2 = 16128488000000.
Part 4 = -27817218000000. Part 5 = 27885760000000.
Part 6 = -10000.0000000000 Part 7 = 300000.00000000
xi = 171058.62068966 yi = 236351.72413793

Subroutine Inlength
Data about Intersection:
Segment: 1
x1 = 170800.00000000 y1 = 236300.00000000
x2 = 171300.00000000 y2 = 236400.00000000
Intersection Point:
xi = 171058.62068966 yi = 236351.72413793
A = 356.57573453473 B = 964.85198756455 C = 246.15956272518
D = 263.74238863410 E = 509.90195135928 F = 608.27625302982

In subroutine Intersection
x1 = 171300.00000000 y1 = 236400.00000000
x2 = 171950.00000000 y2 = 235500.00000000
x3 = 170900.00000000 y3 = 235400.00000000
x4 = 171000.00000000 y4 = 236000.00000000
Part 1 = -22099812000000. Part 2 = 22181945000000.
Part 4 = -36235122000000. Part 5 = 36348720000000.
Part 6 = 90000.000000000 Part 7 = 390000.00000000
xi = 171110.41666667 yi = 236662.50000000

Subroutine Inlength
Data about Intersection:
Segment: 2
x1 = 171300.00000000 y1 = 236400.00000000
x2 = 171950.00000000 y2 = 235500.00000000
Intersection Point:
xi = 171110.41666667 yi = 236662.50000000
A = 671.63836272043 B = 1279.9146157502 C = 1433.9827138467
D = 323.80254828797 E = 1110.1801655587 F = 608.27625302982

In subroutine Intersection
x1 = 171950.00000000 y1 = 235500.00000000
x2 = 171300.00000000 y2 = 235200.00000000
x3 = 170900.00000000 y3 = 235400.00000000
x4 = 171000.00000000 y4 = 236000.00000000
Part 1 = 30198825000000. Part 2 = -30260324000000.

Part 4 = 35966766000000. Part 5 = -36051360000000.
Part 6 = 30000.000000000 Part 7 = -390000.00000000
xi = 170830.55555556 yi = 234983.33333333

Subroutine Inlength
Data about Intersection:
Segment: 3
x1 = 171950.00000000 y1 = 235500.00000000
x2 = 171300.00000000 y2 = 235200.00000000
Intersection Point:
xi = 170830.55555556 yi = 234983.33333333
A = 1030.6903176339 B = 422.41406460403 C = 517.03242728497
D = 1232.9234804488 E = 715.89105316382 F = 608.27625302982

In subroutine Intersection
x1 = 171300.00000000 y1 = 235200.00000000
x2 = 170800.00000000 y2 = 236300.00000000
x3 = 170900.00000000 y3 = 235400.00000000
x4 = 171000.00000000 y4 = 236000.00000000
Part 1 = 24143916000000. Part 2 = -24214019000000.
Part 4 = 27760722000000. Part 5 = -27857440000000.
Part 6 = -110000.00000000 Part 7 = -300000.00000000
xi = 170982.92682927 yi = 235897.56097561

Subroutine Inlength
Data about Intersection:
Segment: 4
x1 = 171300.00000000 y1 = 235200.00000000
x2 = 170800.00000000 y2 = 236300.00000000
Intersection Point:
xi = 170982.92682927 yi = 235897.56097561
A = 103.852043200217 B = 504.42420982961 C = 442.06265757053
D = 766.24193978893 E = 1208.3045973595 F = 608.27625302982
Intersection is real

k = 2 xin(k) = 170982.92682927 yin(k) = 235897.56097561

Intersection Points (In subroutine segment):
Point 1: 171000.00000000 236000.00000000
Point 2: 170982.92682927 235897.56097561
Intersection Points:
Point 1: 171000.00000000 236000.00000000

Point 2: 170982.92682927 235897.56097561

Intersected length = 103.852043200217

Another run => y

FAULT 4:

x1 of fault => 171500
y1 of fault => 235200
x2 of fault => 171750
y2 of fault => 236000
Region (PU,PL,A,B,C,D) => A

... Fault Plane ...
End 1: x = 171500.00000000 y = 235200.00000000
End 2: x = 171750.00000000 y = 236000.00000000
Region: A

x(1) = 170800.0 y(1) = 236300.0
x(2) = 171300.0 y(2) = 236400.0
x(3) = 171950.0 y(3) = 235500.0
x(4) = 171300.0 y(4) = 235200.0
x(5) = 170800.0 y(5) = 236300.0

171500.00000000 235200.00000000 falls outside the region
171750.00000000 236000.00000000 falls outside the region

In subroutine Intersection
x1 = 170800.00000000 y1 = 236300.00000000
x2 = 171300.00000000 y2 = 236400.00000000
x3 = 171500.00000000 y3 = 235200.00000000
x4 = 171750.00000000 y4 = 236000.00000000
Part 1 = -10078252500000.0 Part 2 = 10142720000000.0
Part 4 = -27811224000000. Part 5 = 27899920000000.
Part 6 = -25000.000000000 Part 7 = 400000.00000000
xi = 171913.33333333 yi = 236522.66666667

Subroutine Inlength
Data about Intersection:
Segment: 1
x1 = 170800.00000000 y1 = 236300.00000000

x2 = 171300.00000000 y2 = 236400.00000000
Intersection Point:
xi = 171913.33333333 yi = 236522.66666667
A = 547.59311739851 B = 1385.7458481105 C = 625.47972700072
D = 1135.3816783600 E = 509.90195135928 F = 838.15273071201

In subroutine Intersection
x1 = 171300.00000000 y1 = 236400.00000000
x2 = 171950.00000000 y2 = 235500.00000000
x3 = 171500.00000000 y3 = 235200.00000000
x4 = 171750.00000000 y4 = 236000.00000000
Part 1 = -16094895000000. Part 2 = 16222812500000.
Part 4 = -36045576000000. Part 5 = 36221280000000.
Part 6 = 225000.00000000 Part 7 = 520000.00000000
xi = 171701.34228188 yi = 235844.29530201

Subroutine Inlength
Data about Intersection:
Segment: 2
x1 = 171300.00000000 y1 = 236400.00000000
x2 = 171950.00000000 y2 = 235500.00000000
Intersection Point:
xi = 171701.34228188 yi = 235844.29530201
A = 163.13039725267 B = 675.02233345934 C = 424.69979487818
D = 685.48037068055 E = 1110.1801655587 F = 838.15273071201
Intersection is real

k = 1 xin(k) = 171701.34228188 yin(k) = 235844.29530201

In subroutine Intersection
x1 = 171950.00000000 y1 = 235500.00000000
x2 = 171300.00000000 y2 = 235200.00000000
x3 = 171500.00000000 y3 = 235200.00000000
x4 = 171750.00000000 y4 = 236000.00000000
Part 1 = 36342427500000. Part 2 = -36418760000000.
Part 4 = 35989128000000. Part 5 = -36093840000000.
Part 6 = 75000.000000000 Part 7 = -520000.00000000
xi = 171533.70786517 yi = 235307.86516854

Subroutine Inlength
Data about Intersection:
Segment: 3

x1 = 171950.00000000 y1 = 235500.00000000
x2 = 171300.00000000 y2 = 235200.00000000
Intersection Point:
xi = 171533.70786517 yi = 235307.86516854
A = 725.14337376209 B = 113.00935694992 C = 257.39903035103
D = 458.49202281278 E = 715.89105316382 F = 838.15273071201
Intersection is real

k = 2 xin(k) = 171533.70786517 yin(k) = 235307.86516854

In subroutine Intersection
x1 = 171300.00000000 y1 = 235200.00000000
x2 = 170800.00000000 y2 = 236300.00000000
x3 = 171500.00000000 y3 = 235200.00000000
x4 = 171750.00000000 y4 = 236000.00000000
Part 1 = 30240840000000. Part 2 = -30356547500000.
Part 4 = 27543096000000. Part 5 = -27701680000000.
Part 6 = -275000.00000000 Part 7 = -400000.00000000
xi = 171418.51851852 yi = 234939.25925926

Subroutine Inlength
Data about Intersection:
Segment: 4
x1 = 171300.00000000 y1 = 235200.00000000
x2 = 170800.00000000 y2 = 236300.00000000
Intersection Point:
xi = 171418.51851852 yi = 234939.25925926
A = 1111.3284355367 B = 273.17570482465 C = 1494.7175389558
D = 286.41294159630 E = 1208.3045973595 F = 838.15273071201
Intersection Points:
Point 1: 171701.34228188 235844.29530201
Point 2: 171533.70786517 235307.86516854

Intersected length = 562.01297650942

Another run => n

[Amitava Ghosh, June 7, 1996]

3.2. Simulation of Uniformly Distributed Random Numbers Between [0,1]

Uniformly distributed random numbers between 0 and 1 are simulated using the *drand(k)* function of SUNf77 compiler where k>0 starts a new sequence of random numbers and k = 0 gives the next random number in the sequence. *drand(k)* function gives the double precision random numbers.

Using these random numbers, a set of random numbers uniformly distributed between [a,b] can be generated from

$$y = (b - a)\, x + a$$

where,
x = uniform random number between [0,1]
y = uniform random number between [a,b].

A subroutine to generate uniformly distributed random numbers between [0,1], called *random*, is left in the file *fault.f* although it was not used to generate the uniformly distributed random numbers. This subroutine may be used in place of the *drand(k)* function with some modifications of the procedure for calling for the random number in *fault.f* as this subroutine requires the previous random number as seed for generation for next random number.

[Amitava Ghosh, June 27, 1996]

3.3. Simulation of Normally Distributed Random Numbers

A subroutine *gauss* has been developed following the mathematical guideline given in Section 2.1.4 and adopting the routine given in Ghosh and Kulatilake (1987). A set of 500 normally distributed random numbers with a probability 90% falling between [-1, 1] was generated. The statistics of the generated numbers are given below:

	Input Data	**Normal(3.74e-3,0.59)**
Minimum	-1.584767	
Maximum	1.966892	
Mode	-0.128587	3.743165e-3
Mean	3.743165e-3	3.743165e-3
Std Deviation	0.586337	0.586337
Variance	0.343791	0.343791
Skewness	0.119546	0.0
Kurtosis	3.05641	3.0

Best Fit Results

C-S Test	57.136959
K-S Test	0.023695
A-D Test	0.231722

Figure 3-4 shows the histogram of random numbers with a fitted normal distribution with mean and standard deviation equal to 0.0037 and 0.5863 respectively. They compare very well with the population mean and standard deviation equal to 0.0 and 0.6079 respectively. The skewness and kurtosis of the data set indicate normality. Figure 3-5 shows the cumulative distribution of these numbers. The numbers were tested for normality. The data set passes Kolmogorov-Smirnov (K-S) test for goodness-of-fit with α = 0.05. As expected, with a larger set of random numbers, the sample mean and standard deviation become closer to the population mean and standard deviation. This has been tested with different data sets. For example, when the number of generated random numbers is 1000, the sample mean and standard deviation are 0.0012 and 0.5987 respectively, as shown below. The skewness and kurtosis of the data set have improved quite a bit.

	Input Data	**Normal(1.25e-3,0.60)**
Minimum	-2.051897	
Maximum	1.859709	
Mode	-0.056978	1.249021e-3
Mean	1.249021e-3	1.249021e-3
Std Deviation	0.598718	0.598718
Variance	0.358463	0.358463
Skewness	-0.012203	0.0
Kurtosis	2.969442	3.0

Best Fit Results

C-S Test	37.568098
K-S Test	8.731377e-3
A-D Test	0.077632

[Amitava Ghosh, June 28, 1996]

3.4. Simulation of Beta Distributed Random Numbers

A subroutine *betad* has been developed following the mathematical guideline given in Section 2.1.5 with any acceptable values of α and β. In the file *fault.inc*, the values of α and β are fixed as 1.5 and 3.0, as given in Stirewalt et al. (1995). A set of 1000 random numbers between [0, 1] was generated. Sample statistics show that sample α and β are 1.50 and 3.11 respectively. Sample mean and variance are 0.3279 and 0.0390 respectively which compare very well with population mean of 0.3333 and population variance of 0.0404. Figure 3-6 shows the histogram of random numbers with beat distribution fitted over

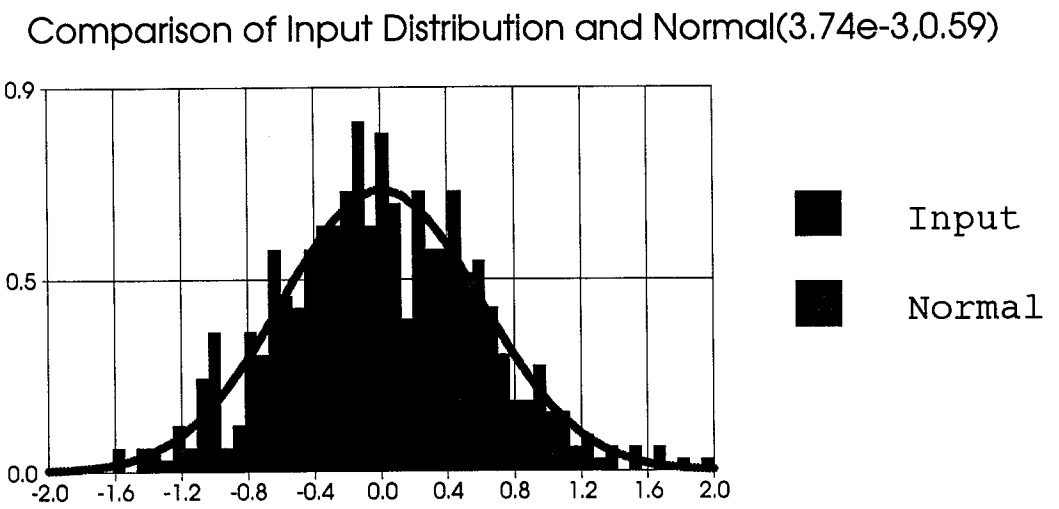


Figure 3-4 Histogram of random numbers, generated by *gauss*, having normal distribution

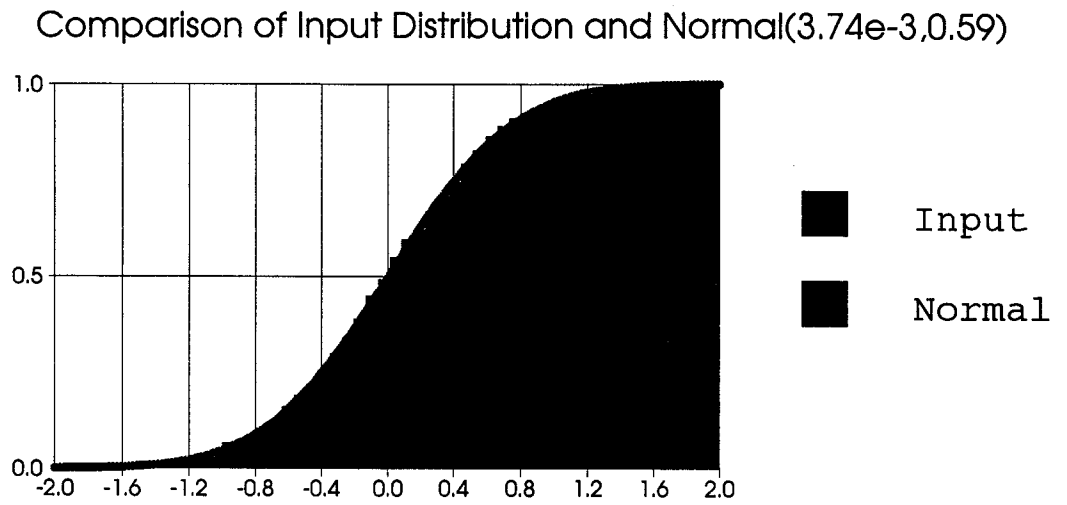
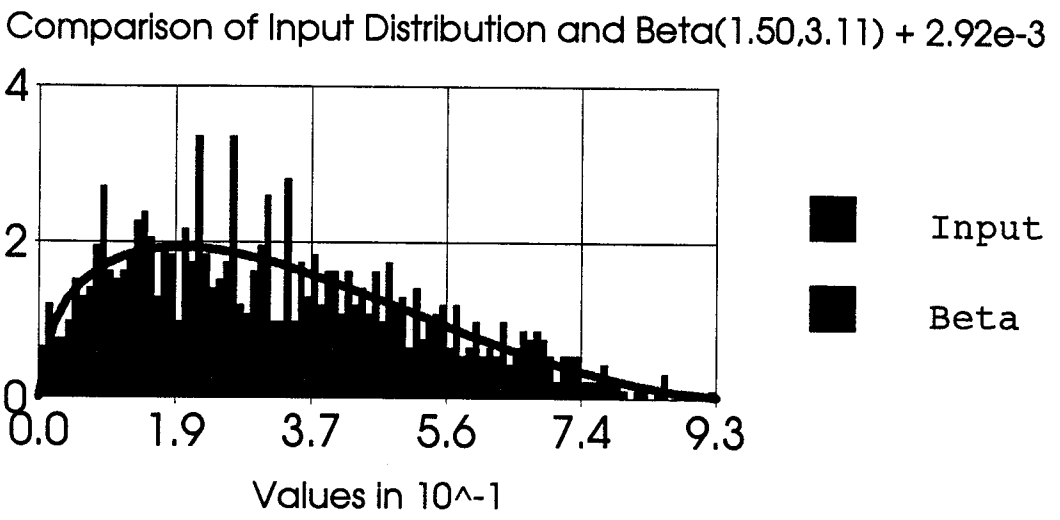


Figure 3-5 Cumulative distribution of random numbers generated by *gauss* having normal distribtuion



No. of data points = 1000

Figure 3-6 Histogram of random numbers generated by *betad* having beta distribution

it.

	Input Data	Beta(1.50,3.11) + 2.92e-3
Minimum	2.91705e-3	
Maximum	0.92994	
Mode	0.206862	0.191073
Mean	0.327924	0.325007
Std Deviation	0.197694	0.197694
Variance	0.039083	0.039083
Skewness	0.485402	0.535402
Kurtosis	2.421904	3.38095

Best Fit Results

C-S Test	13.767742
K-S Test	0.013351
A-D Test	0.258163

[Amitava Ghosh, June 28, 1996]

4. OTHER FEATURES

4.1. Date and Time Stamp

This code will write the date and time of running on the output file. It uses the *fdate()* function from the SUNf77 library.

[Amitava Ghosh, June 27, 1996]

4.2. File for Plotting the Faults and the Repository Region

At present, CNWRA does not have any software which can plot the faults and the repository while the module is running. Only available software is a freeware called PLOTMTV which does a decent job in plotting the faults from a data file. It requires the data in a certain format with several lines of header information for formatting and manipulating the visual look of the plot. The FAULTING module automatically writes the necessary information to the plotting files for processing by PLOTMTV. In most cases, the plot file will run without any modification on PLOTMTV and produce a decent plot. User may want to change the plot file for enhancement of the plot. PLOTMTV can produce a postscript output for

plotting on postscript printer. Present setup in the FAULTING module only produces black and white output. With trivial modification and proper setting of PLOTMTV program, a color output can be generated.

[Amitava Ghosh, June 27, 1996]

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[Amitava Ghosh, June 28, 1996]

CENTER FOR NUCLEAR WASTE REGULATORY ANALYSES

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SCIENTIFIC NOTEBOOK
Development of the FAULTING Module

by

Amitava Ghosh

Southwest Research Institute
Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas

October 17, 1996

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1. INITIAL ENTRIES

Scientific NoteBook: # 167

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Project Title: Development of the FAULTING Module of Phase 3 IPA

Project Staff: Amitava Ghosh

By agreement with the CNWRA QA this NoteBook is to be printed at approximate quarterly intervals. This computerized Scientific NoteBook is intended to address the criteria of CNWRA QAP-001.

[Amitava Ghosh, February 28, 1996]

1.1. Objectives

The objective of this activity is to develop the FORTRAN coding of the faulting consequence (FAULTING) module for the Phase 3 of the Nuclear Regulatory Commission (NRC) Iterative Performance Assessment (IPA) activity. The basic approach to the FAULTING module has been described in Stirewalt et al. (1995). Taking into account the published data for faults at Yucca Mountain area, this module provides a framework for determining if the primary fault displacement (that is, displacement along the main fault trace rather than along associated secondary fractures) in the repository block could induce waste package disruption, the timing of that disruption, and the number of waste packages disrupted.
[Amitava Ghosh, February 28, 1996]

1.2. Technical Approaches

The codes for the FAULTING module will be written in Fortran 77. Fault displacement is generated in the FAULTING module along an assumed, unknown, and randomly located fault zone inside the simulation area. These unknown fault zones include those not distinguished or adequately characterized, as well as new faults which may develop during the 10,000 year regulatory time frame of interest. Strike direction is determined as either northeast or northwest observed in the field at and near Yucca Mountain. Whether the fault intersects the potential repository depends on location and orientation of the fault in the simulation area and total fault trace length. Whether waste packages are disrupted is dependent upon amount of displacement exceeding a threshold value which is governed by repository and waste package design and waste package emplacement geometry. If the threshold displacement is exceeded by either

largest credible displacement in a single event or by smaller cumulative displacements with time through multiple events, then number and locations of waste packages intersected and disrupted can be calculated based on length of intersection of the fault zone with the repository, repository design, and waste package emplacement geometry. Location, trace orientation, geometry, activity, number and time and amount of largest credible displacement faulting events, and amount and time of cumulative displacements are chosen randomly from range of published data represented as probability distribution functions (PDFs). It is assumed that the unknown fault zones can possess attributes similar to those of the Ghost Dance and Sundance faults. The fault zone is assigned a randomly selected width, and displacement in the zone is considered along both single and multiple slip surfaces. It is assumed that the variation in dip of the fault has little influence on number of waste packages disrupted, considering horizontal emplacement. If waste package disruption occurs as a result of either a largest credible displacement event or cumulative displacement, the timing of that disruption is relayed to the SOurce TErm Code (SOTEC) for calculation of radionuclide release.

The random numbers following a particular PDF will be generated primarily using the program LHS94 (version 1.1) (Iman and Shortencarier, 1984) which uses the Latin Hypercube method. However, using the LHS94 program is a two step process. All the random numbers needed to run the FAULTING modules should be known beforehand and need to generated in advance of running the module. The final version of the FAULTING module will have an user interface to do this. Additionally, each subroutine of the FAULTING module may use own random number generation routines during development. Currently, the LHS94 code is not under the code configuration management of CNWRA.

[Amitava Ghosh, February 28, 1996]

The code in the present form has own subroutines to generate necessary random numbers from a given distribution. Therefore, at this point, there is no need to generate the random numbers using the LHS routines before the run and use them while running this module. At present, this is quite a cumbersome process as we have to estimate beforehand how many random numbers from each specific distribution is needed. It may also be extremely difficult to guess beforehand as the number of random numbers needed for any simulation drastically goes down if the generated fault does not intersect the given repository region.

[Amitava Ghosh, June 27, 1996]

It was also decided to carry out the complete calculation in double precision. The reason is as follows. In the calculation done by this module, we are dealing with very large numbers (coordinates of the faults) and very small numbers (slipping rate on a fault surface). In both cases, it becomes necessary to keep enough precision in the calculations (at least more than 6 significant digits) so that rounding off error does not mislead the calculation sequence.

[Amitava Ghosh, June 27, 1996]

1.3. Computers, Computer Codes, and Data Files

Table 1-1. Computer, operating system, and compiler to be used in developing FAULTING module

Machine Name	Machine Type	Operating System	Compiler	Location
snowwhite	SUN SPARCstation 20	SUNOS 4.1	f77 (SUN)	Building 189

[Amitava Ghosh, February 28, 1996]

1.4. Mathematical Theory

Not Applicable

[Amitava Ghosh, February 28, 1996]

Two modifications of the algorithm given in Stirewalt et al. (1995) were carried out in this period:

1. Flow chart for calculation of largest credible displacement along single and multiple slip surfaces given in Stirewalt et al. (1995) has been modified to (i) reduce unnecessary calculations, and (ii) carry out the sequence of calculations in a more logical way.

Previously, after randomly generating the largest credible displacement, this amount of displacement was partitioned among 2 to 4 randomly generated slip surfaces of the same fault plane. Thereafter, the slip along each of the multiple surfaces was compared against the threshold value. If failure occurs on any of the multiple slip surfaces of the fault plane, the check for slippage on the fault plane itself. This procedure has been modified to allow the flow of calculation in a more logical way and to eliminate unnecessary calculations.

In the present procedure, once the largest credible displacement is randomly generated for a given fault plane, the displacement is compared with the threshold displacement TD for waste packages, based on a uniform pdf varying between 0.1 and 0.5 m. If only failure is indicated, the total displacement on this fault plane is partitioned among 2 to 4 slip surfaces generated randomly. Displacement on each of these slip surfaces is compared with the threshold displacement TD.

New flow chart is given in Figure 1-1. The code necessary to determine the number of waste packages being disrupted due to the faulting event is under development.

[Amitava Ghosh, August 18, 1996]

2. Previously, comparison of displacement along any of the slip surfaces was carried out against LDmax, which was set to 0.045 m. This is not correct as the correct comparison should be against the threshold displacement for waste package rupture, TD. The code has been modified to reflect this.

[Amitava Ghosh, August 18, 1996]

1.5. Assumptions

The assumptions for each of the parameters and the complete module are given in Stirewalt et al. (1995). [Amitava Ghosh, February 28, 1996]

1.6. Initial/Boundary Conditions

Not Applicable [Amitava Ghosh, February 28, 1996]

2. DEVELOPMENT OF THE FAULTING MODULE

2.1. Mathematical Theory

2.1.1. Coordinates of the Point of Intersection of Two Straight Lines Defined by the Coordinates of the End Points

Line 1: End points are (x_1,y_1) and (x_2,y_2)
Line 1: End points are (x_3,y_3) and (x_4,y_4)
Intersection point: (x_i,y_i)

Equation of line 1:

$$\frac{y-y_1}{x-x_1}=\frac{y_2-y_1}{x_2-x_1} \tag{1}$$

It goes through (x_i,y_i). Therefore,

Similarly,

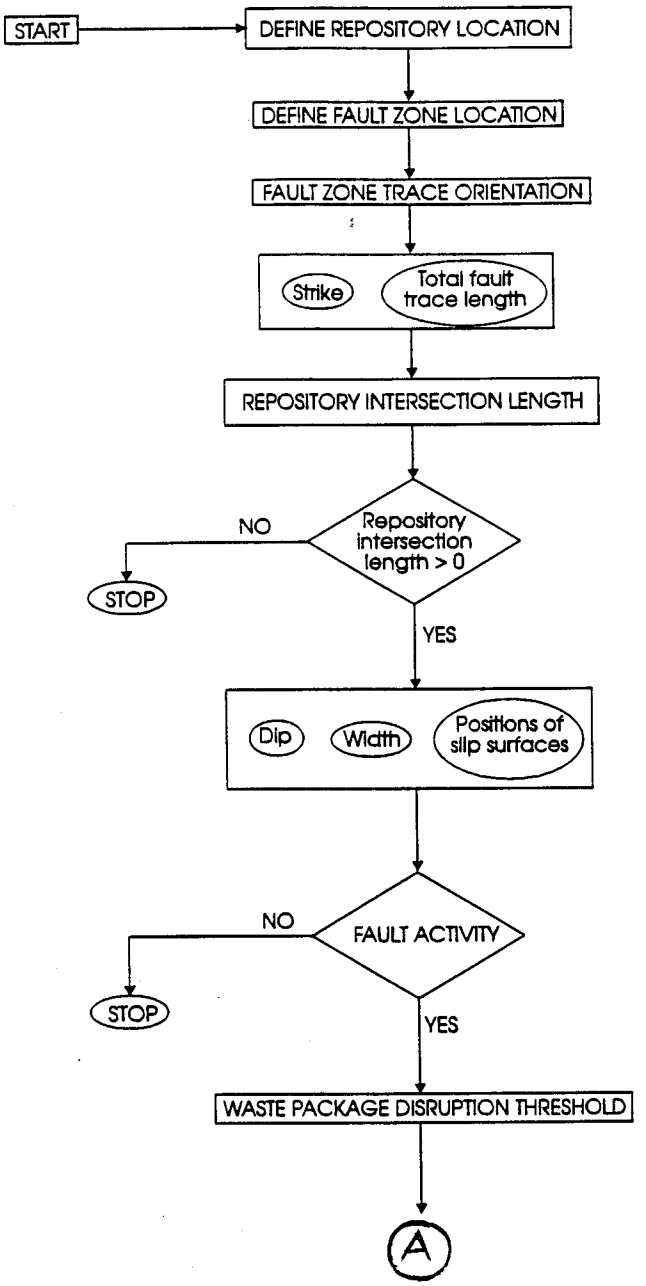


Figure 1-1. Flow diagram illustrating sequential steps for describing faulting events

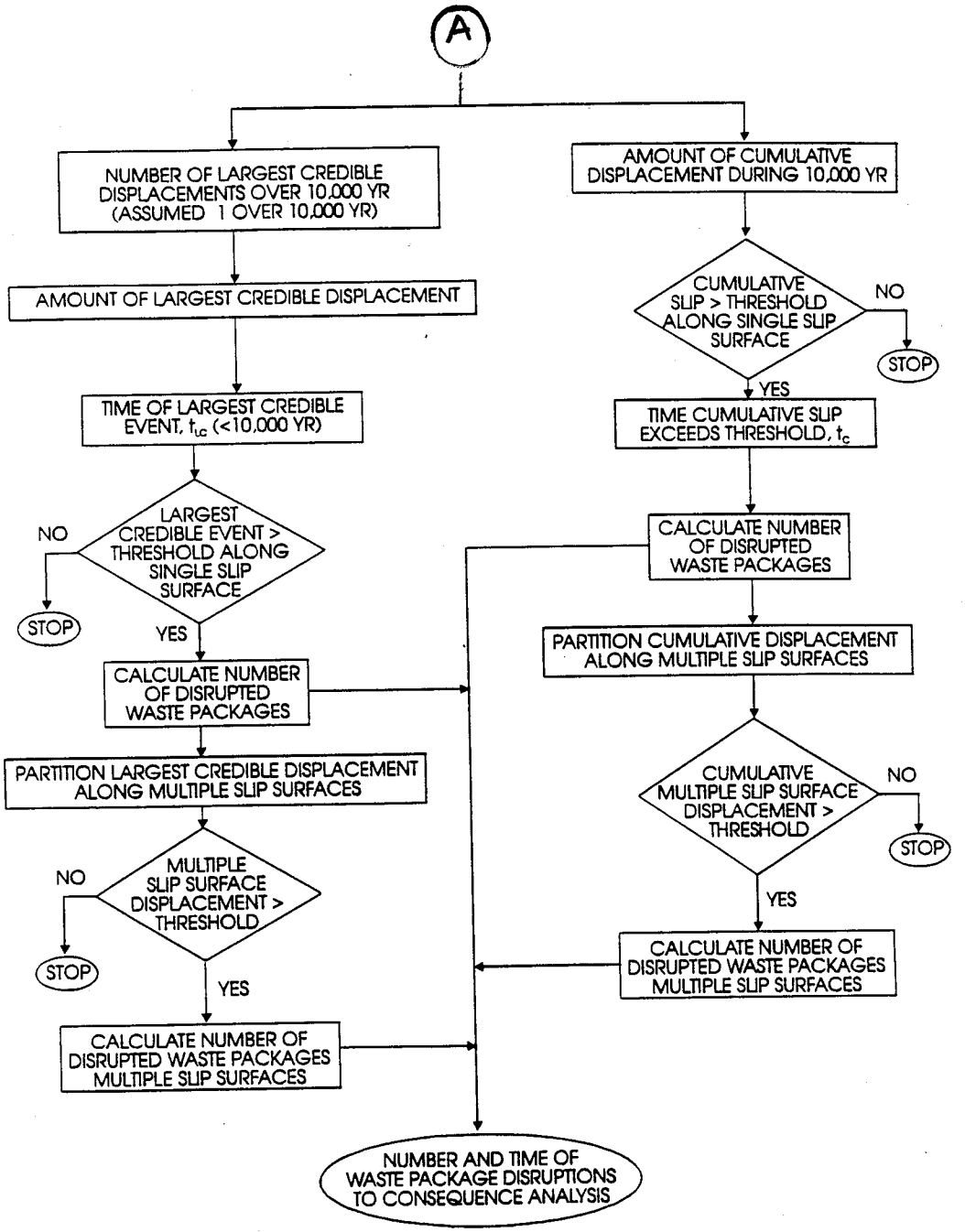


Figure 1-1. Flow diagram illustrating sequential steps for describing faulting events (cont.)

$$\frac{y_i - y_3}{x_i - x_3} = \frac{y_4 - y_3}{x_4 - x_3} \tag{3}$$

Solving (2) and (3) for x_i and y_i, we get

$$x_i = \frac{(x_1 - x_2)(x_3 y_4 - x_4 y_3) + (x_3 - x_4)(x_1 y_2 - x_2 y_1)}{-(x_3 y_1 - x_4 y_1 - x_3 y_2 + x_4 y_2 - x_1 y_3 + x_2 y_3 + x_1 y_4 - x_2 y_4)}$$

$$y_i = -\frac{x_2 y_1 y_3 + x_4 y_1 y_3 + x_1 y_2 y_3 - x_4 y_2 y_3 + x_2 y_1 y_4 - x_3 y_1 y_4 - x_1 y_2 y_4 + x_3 y_2 y_4}{-x_3 y_1 + x_4 y_1 + x_3 y_2 - x_4 y_2 + x_1 y_3 - x_2 y_3 - x_1 y_4 + x_2 y_4}$$

These solutions were also verified using the commercial program Mathematica. These equations were coded in the subroutine intersection.

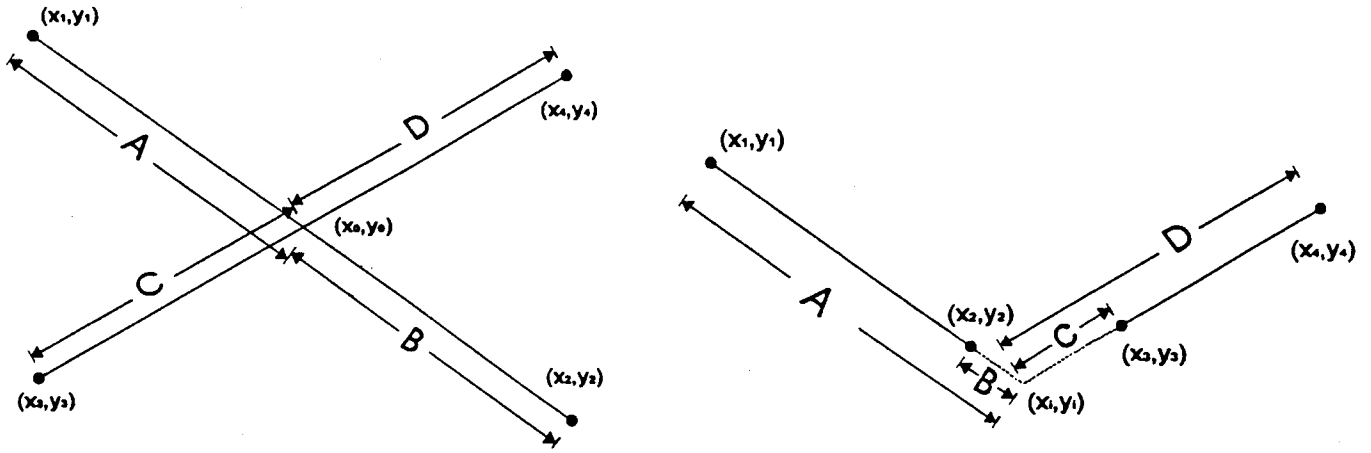


Figure 2-1. Determination of real intersection point of two finite straight lines

$$\frac{y_i - y_1}{x_i - x_1} = \frac{y_2 - y_1}{x_2 - x_1} \tag{2}$$

These equations do not guarantee that the point of intersection of these lines are real, that is, the point lies on both the lines as shown:

A = length of the line joining (x_1,y_1) and (x_i,y_i)
B = length of the line joining (x_2,y_2) and (x_i,y_i)
C = length of the line joining (x_3,y_3) and (x_i,y_i)
D = length of the line joining (x_4,y_4) and (x_i,y_i)
E = length of the line joining (x_1,y_1) and (x_2,y_2)
F = length of the line joining (x_3,y_3) and (x_4,y_4)

For the intersection to be real, either of the following two conditions needs to be true.

$$A + B = E \Rightarrow (A + B) - E = 0$$

or,

$$C + D = F \Rightarrow (C + D) - F = 0$$

It should be recognized that comparison of real numbers having very similar magnitudes is problematic due to round off errors. Therefore, an acceptable tolerance should be used.

[Amitava Ghosh, March 31, 1996]

The formula for x_i has been changed to be parallel with that of y_i so that the coding of the subroutine becomes easier. The revised formula is as follows:

$$x_i = \frac{-x_2x_4y_3 + x_1x_4y_3 + x_2x_4y_1 - x_2x_3y_1 - x_1x_4y_2 + x_1x_3y_2 + x_2x_3y_4 - x_1x_3y_4}{-x_3y_1 + x_4y_1 + x_3y_2 - x_4y_2 + x_1y_3 - x_2y_3 - x_1y_4 + x_2y_4}$$

For the intersection to be real, both of the above two conditions needs to be true. Otherwise, in some cases wrong conclusions will be made. This has been corrected in the code.

[Amitava Ghosh, May 23, 1996]

2.1.2. Determination whether a given point falls within a quadrilateral defined by the four corners

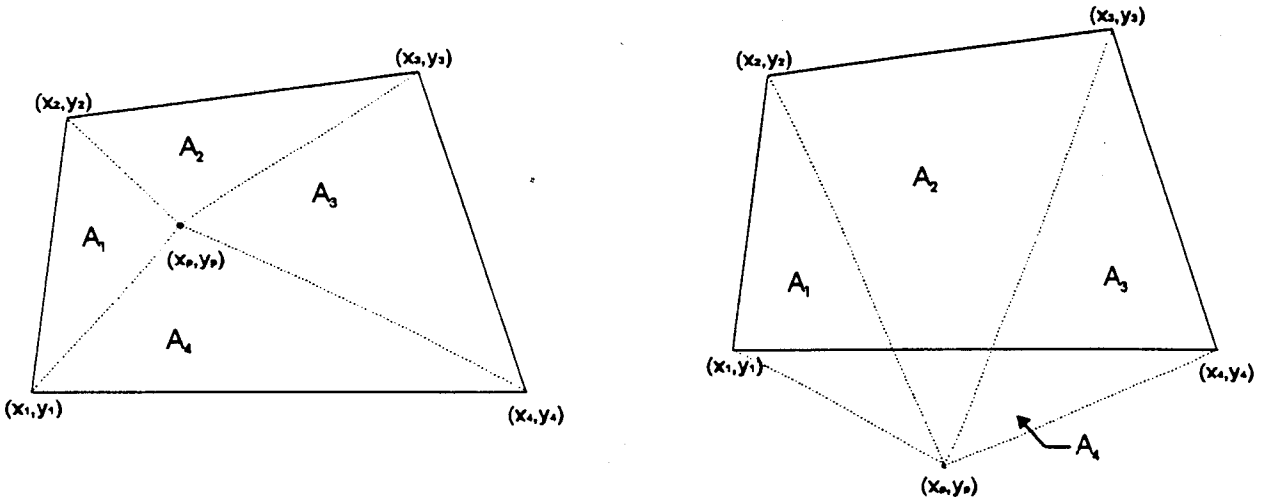


Figure 2-2. Determination whether a given point falls within a given quadrilateral

Given point is (x_p,y_p). The quadrilateral has corners defined by (x_1,y_1), (x_2,y_2), (x_3,y_3), and (x_4,y_4).

A1: area of triangle (x_1,y_1), (x_2,y_2), (x_p,y_p)
A2: area of triangle (x_2,y_2), (x_3,y_3), (x_p,y_p)
A3: area of triangle (x_3,y_3), (x_4,y_4), (x_p,y_p)
A4: area of triangle (x_4,y_4), (x_1,y_1), (x_p,y_p)

Area of quadrilateral (x_1,y_1), (x_2,y_2), (x_3,y_3), (x_4,y_4) = A
= area of [triangle (x_1,y_1), $x_2,y_2)$, (x_3,y_3) + triangle (x_3,y_3), (x_4,y_4) (x_1,y_1)]

If the point (x_p,y_p) is inside the quadrilateral, then

$$A = A_1 + A_2 + A_3 + A_4$$

If outside,

$$A < (A_1 + A_2 + A_3 + A_4)$$

[Amitava Ghosh, March 31, 1996]

2.1.3. Determination of the Fault Length Intersected by the Repository Block

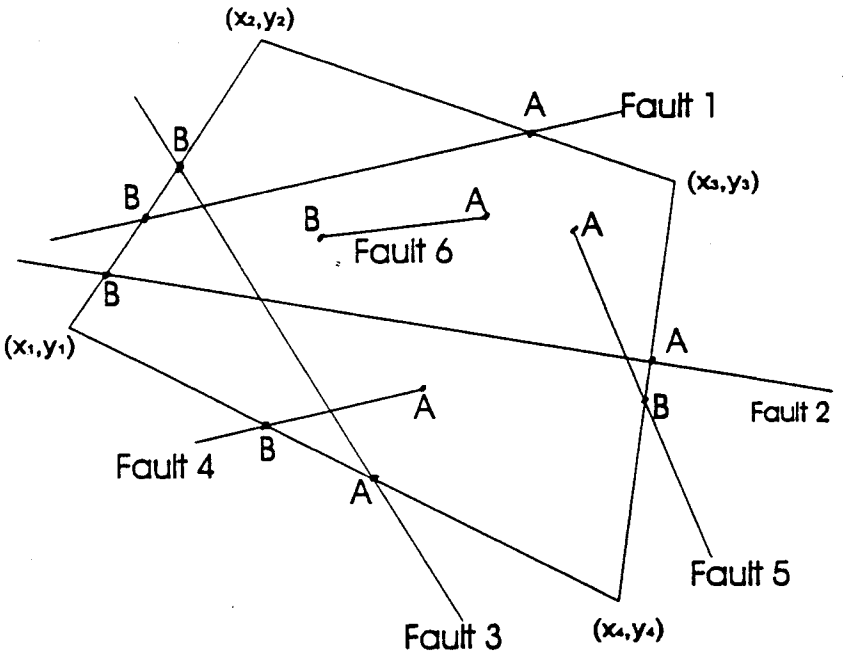


Figure 2-3. Determination of the length of a given fault intersected by a repository block

- Fault 7: Intersection length = Fault length
- Fault 5, Fault 6: Intersection length = AB: need to find only B
- Fault 1, Fault 2, Fault 3, Fault 4: Intersection Length = AB: need to know both A and B

Known: (i) Two ends of each fault (xf_1,yf_1) and (xf_2, yf_2)
(ii) Four corners (x_1,y_1), (x_2,y_2), (x_3,y_3), (x_4,y_4)

Step 1: Determine whether each end of the fault is within the boundary
if yes, intersection length = fault length

Step 2: If one end is within the boundary, determine

(i) which segment it is intersecting
(ii) calculate length AB

Step 3: If both ends are outside the boundary, determine
(i) which segments it is intersecting
(ii) calculate length AB

[Amitava Ghosh, March 31, 1996]

The length of the portion of a randomly generated fault intersected by a given repository region is calculated following the above-mentioned algorithm. Subroutine *checkin* is used to determine whether both ends of the fault fall within the given region. If both ends of the fault are within the given region then the intersected length is the length of the fault. If one end or both ends fall outside the given region, then subroutine *inlength* is called to determine first the intersection point(s) of the fault and the sides of the quadrilateral region. There will be one or two real intersection points depending on whether one or two end points fall outside the region, respectively. The intersected length for the first case is the distance between the real intersection point and the other end point of the fault which falls within the region. The intersected length for the second case is the distance between the two intersection points.

[Amitava Ghosh, June 7, 1996]

2.1.4. Random Numbers Having Normal Distribution with Mean μ and Standard Deviation σ, N (μ, σ_2)

Random numbers have to be generated with mean μ and standard deviation σ so that there is 90 percent probability that the number will fall between A and B.

$$\mu = \frac{A+B}{2}$$

$$P(x \le A) = \frac{100-90}{2}\% = 5\% = 0.05$$

$$P(X \ge B) = 0.05$$

$$P(Z \le 1.645) = 0.05$$

For a standard normal variate Z,

$$P(Z \le 1.645) = 0.05$$

Standard deviation of the desired truncated normal distribution is $\sigma = \frac{X-\mu}{1.645} = \frac{B-\mu}{1.645} = \frac{B-A}{2.29}$

Generation of normally distributed random numbers is carried out following Ang and Tang (1984):

If U_1 and U_2 are two uncorrelated uniformly distributed random numbers between 0 and 1, then two normally distributed random numbers with mean μ and standard deviation σ are:

$$x_1 = \mu + \sigma\sqrt{-2lnU_1}\,\mathrm{Cos}2\pi U_2$$
$$x_2 = \mu + \sigma\sqrt{-2lnU_1}\,\mathrm{Sin}2\pi U_2$$

[Amitava Ghosh, March 31, 1996]

Standard deviation of the desired truncated normal distribution is $\sigma = \frac{X-\mu}{1.645} = \frac{B-\mu}{1.645} = \frac{B-A}{3.29}$

This is the corrected form of the equation as 2x1.645 is equal to 3.29, not 2.29 as typed.

[Amitava Ghosh, May 21, 1996]

2.1.5. Beta Distribution in the Interval (A, B) with Parameters α and β

Random numbers Y from a general Beta distribution with lower and upper bounds A and B, respectively, may be obtained through

$$Y = \frac{X-A}{B-A}$$

where X is the corresponding random number for the standard Beta distribution

$$\mu_x = \frac{\alpha}{\alpha+\beta}$$
$$\sigma_x = \frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}$$

Therefore, $\mu_y = (B-A)\mu_x + A = \frac{A\beta + B\alpha}{\alpha+\beta}$

$$\sigma_y = (B-A)^2\sigma_x = \frac{(B-A)^2\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}$$

Generation of Beta distributed random numbers is carried out following Ang and Tang (1984):

A random number X with pdf of the standard Beta distribution with shape parameters σ and β can be generated from

$$X=\frac{U_1^{1/\alpha}}{U_1^{1/\alpha}+u_2^{1/\beta}}$$

where U_1 and U_2 are two random numbers having the standard uniform distribution provided $U_1^{1/\alpha}+U_2^{1/\beta}\le 1$.

[Amitava Ghosh, March 31, 1996]

2.1.6. LogBeta Distribution in the Interval (A, B) with Parameters α and β

X is standard beta distributed with mean equal to 0 and standard deviation equal to 1. Then Y has logbeta distribution if

$$Y = e^X$$

which means

$$\ln Y = X$$

has beta distribution. Consequently, the lower and upper limits will be:

$$a^* = \ln a$$

$$b^* = \ln b$$

Now, we have to generate a standard beta distribution with lower and upper limits are a^* and b^* respectively.

Mean of logbeta distribution $\mu = e^{\frac{\alpha}{\alpha+\beta}}$

Variance of logbeta distribution $\alpha = e^{\frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}}$

Given $\alpha = 1.5, \quad \beta = 3.0$

$\mu = e^{\frac{1.5}{4.5}} = 1.3956$

$\sigma = e^{\frac{1.5x3}{4.5^2x(5.5)}} = 1.0412$

Minimum value $= e^0 = 1$

Maximum value $= e^1 = 2.71828$

Therefore, standard Beta x, i.e., within interval (0,1) distribution, when converted to logbeta distribution Y, will be within the interval (1, 2.71828)

$$Y = \frac{x-a}{b-a} = \frac{x-1}{1.71828}$$

Y will be logbeta distributed with interval between (0,1)

If, for example, we want random numbers which is logbeta within interval (A,B), then:

$$Z = Y(B-A)+A$$

$$Z = \frac{x-a}{b-a}\cdot(B-A)+A$$

$$= \frac{(x-a)(B-A)+A(b-A)}{b-a} = \frac{x(B-A)}{b-a} - \frac{a(B-A)}{b-a} + A$$

$$= x\frac{B-A}{b-a} + \frac{-aB+aA+bA-aA}{b-a}$$

$$= x\frac{B-A}{b-a} + \frac{bA-aB}{b-a}$$

[Amitava Ghosh, June 7, 1996]

2.1.7. Representation of Dip Angle

The given definition of dip given in Stirewalt et al. (1995) is quite inconvenient for computer processing. Dip direction and dip angle would have been a better alternative way of expressing the orientation of fault planes. Unfortunately, the data given here do not have correspondence between the strike and dip of a given fault plane. The field observation is restricted to the distribution of fault dip in two dominant fault orientations, namely, northwest (NW) and northeast (NE). For example, a dip of 60W does not belong to the plane with a particular fault with a given strike. Rather the data give the distribution of strike and dip independently.

A scheme has been devised here to express dip without any other information of direction, e.g., NW, NE, or W. As the faults are striking NE or NW, they will dip either to east or west. Therefore, in this scheme, the dip angle is always measured from the East direction. In other words, dip angle 0 degree and dipping towards east is dip 0. Similarly, dip angle 0 degree and dipping towards west is dip 180 degree. A dip angle of 30 degree and dipping east is dip 30 and dipping west is dip 120 degree.

It should be noted here that this scheme is not quite general and will not work if a fault has the strike towards east. In Yucca Mountain region, the fault orientation is either NE or NW. Therefore, this scheme will work without any problem. A better scheme is necessary to make this code more general and applicable to any other region.

[Amitava Ghosh, June 7, 1996]

2.2. Input Data

2.2.1. Simulation and Repository Regions

The FAULTING module requires information about the origin of the simulation area and the boundaries of different repository blocks which are given in terms of the coordinates of the four corners.

The origin of the simulation area was taken as 170500 m East and 233000 m North, which falls in the middle of the primary emplacement area. Different emplacement areas are given by (TRW Environmental Safety Systems Inc., 1995):

Region Primary Upper:
[(170500E, 234800N), (171300E, 234500N), (171100E, 231100N), (169800N, 231500E)]

Region Primary Lower:

[(171600E, 233700N), (172300E, 233300N), (171700E, 232000N), (171500E, 232100N)]

Optional Region A:
[(170800E, 236300N), (171300E, 236400N), (171950E, 235500N), (171300E, 235200N)]

Optional Region B:
[(169000E, 236800N), (169700E, 236500N), (169400E, 234500N), (168500E, 234800N)]

Optional Region C:
[(168300E, 234500N), (168900E, 234200N), (168200E, 232200N), (167600E, 232500N)]

Optional Region D:
[(169200E, 234200N), (169700E, 234000N), (169100E, 231500N), (168200E, 231700N)]

[Amitava Ghosh, March 31, 1996]

Figure 2-4 is from TRW Environmental Safety Systems Inc. (1995) showing the emplacement regions. Figure 2-5 shows the plots of the regions given by the above-listed coordinate points.

[Amitava Ghosh, June 7, 1996]

2.2.2. Development of Parameter File *fault.inc*

This code requires many site-specific values for different parameters. Previously, the values of these parameters were defined inside the code at the appropriate places where they were first defined. This may be helpful to read the code but has potential danger of accidentally modifying the parameters values during some modification of the code. Consequently, all these constants are declared in a separate file called *fault.inc* which is included in this code at the beginning of compilation. Any modification to the parameters can be done independently in the file *fault.inc* without any possibility of modifying any part of the code accidently. The content of the file *fault.inc* is given below:

```
c
c....C*****************************************************************
c      This file contains values of different variables used in the
c      FAULTING module. Any change to the data should be done here
c      so that the program remains unaffected.
c....C*****************************************************************
c


c
c... Coordinates of the square region (meter)
```

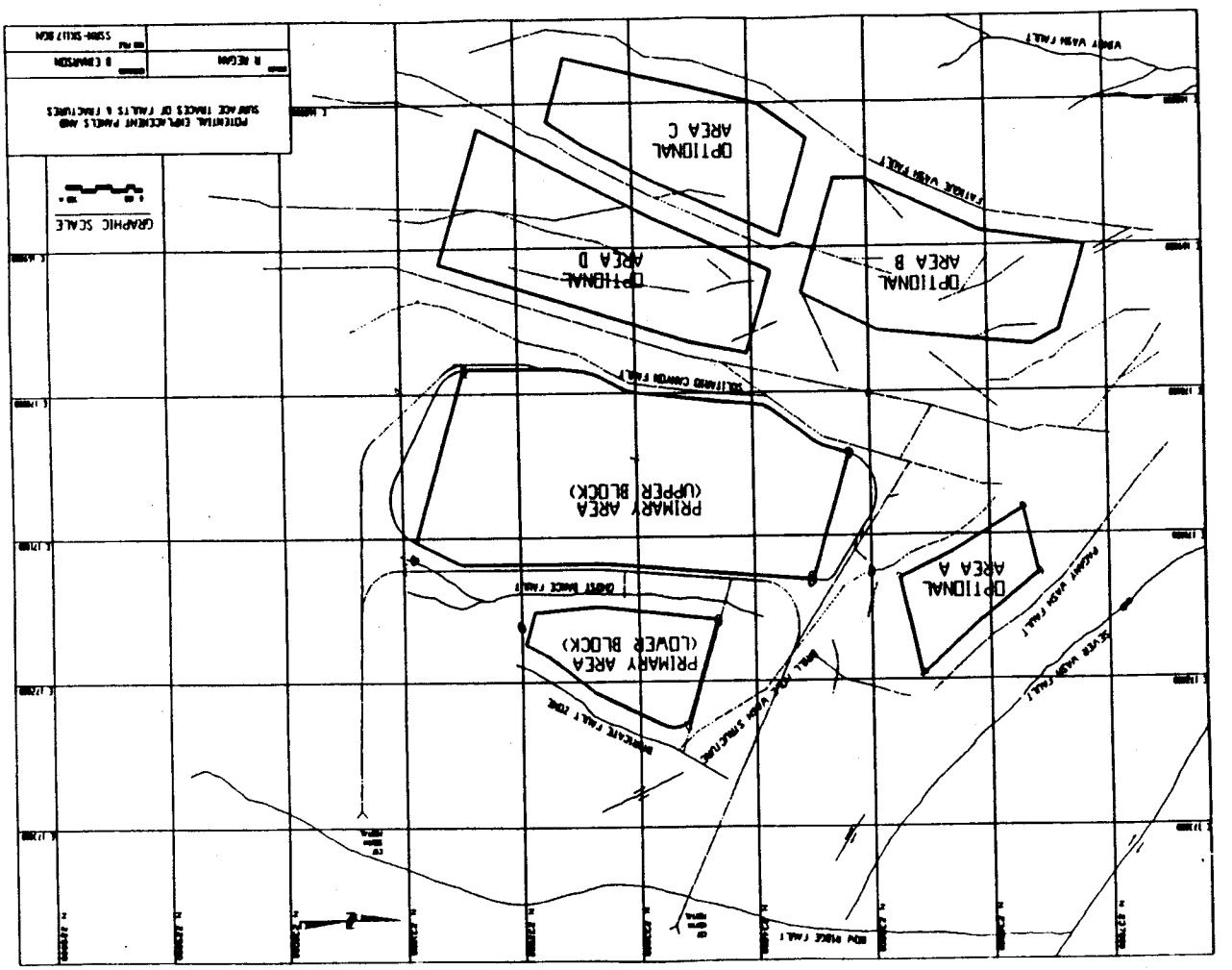


Figure 2-4 Different repository blocks (TRW Environmental Safety Systems Inc., 1995)

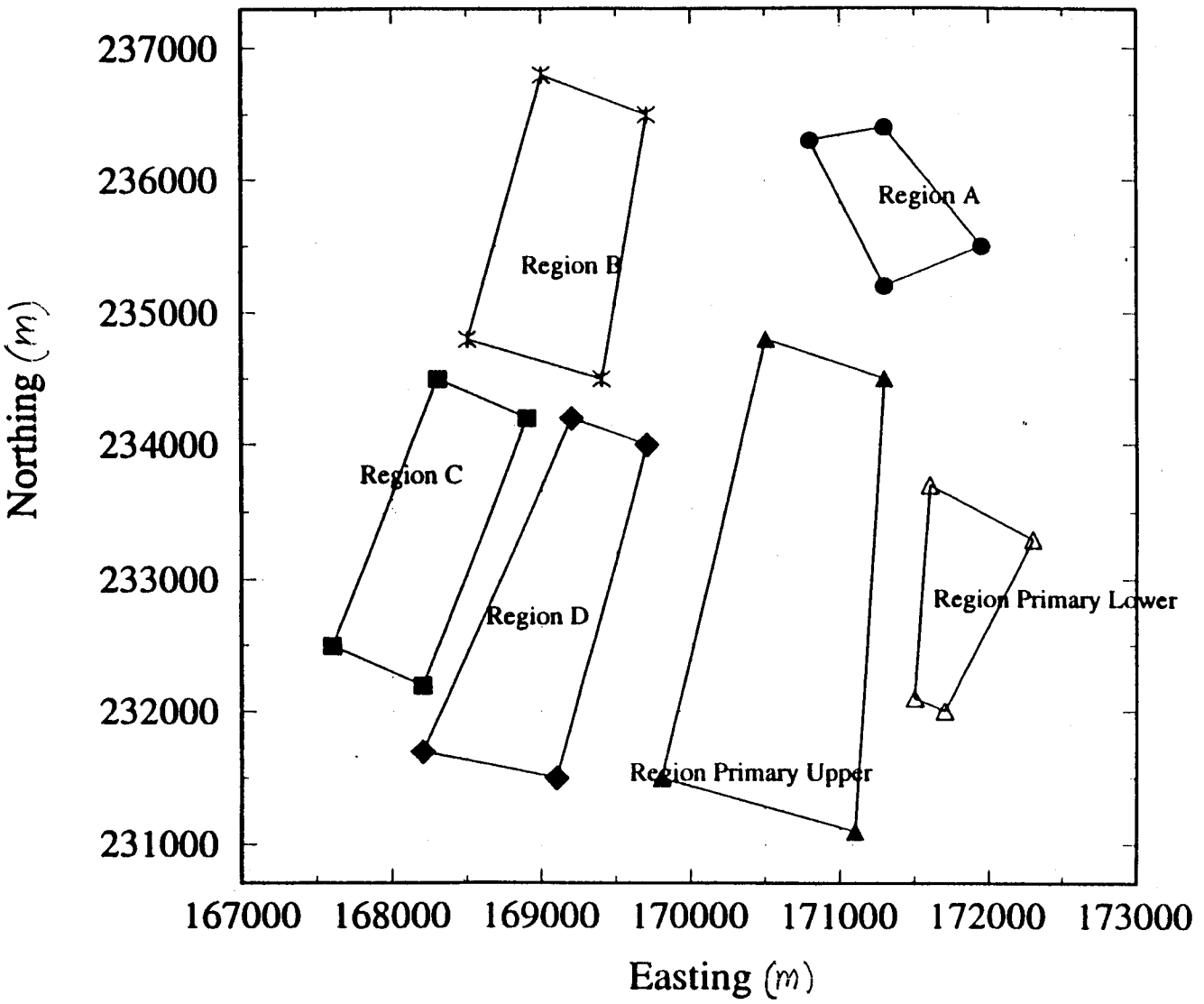


Figure 2-5 Different repository blocks as modeled in the FAULTING module

```
c
c
c     Define the coordinates of the square region
c     Origin is defined in the middle of the Primary Area (Upper Block)
c     x0 = 170500 East = 170500m, y0 = 233000 North = 233000 m
c     The simulation block is 50km x 50 km centered at (x0,y0)
c

      xleft   = 145500.0
      xright  = 195500.0
      ybottom = 208000.0
      ytop    = 258000.0

c
c... Probability of fault zone orientation
c

      pforient = 0.25

c
c... Strike of fault zone (degree, measured from North)
c

      min_SNW = 115.0d0
      max_SNW = 130.0d0

      min_SNE = 65.0d0
      max_SNE = 95.0d0

c
c... Total trace length (meter)
c

      min_ltNW = 2000.0d0
      max_ltNW = 10000.0d0

      min_ltNE = 3000.0d0
      max_ltNE = 12000.0d0

c
c... Dip angle (degree, measured from East)
c
```

```
      min_thetaNW = 80.0d0
      max_thetaNW = 100.0d0

      min_thetaNE = 90.0d0
      max_thetaNE = 120.0d0

c
c...  Fault Width (meter)
c

      min_wNW = 0.5d0
      max_wNW = 275.0d0

      min_wNE = 0.5d0
      max_wNE = 365.0d0

      alpha = 1.5d0
      beta = 3.0d0

c
c...  Time of coourance of largest credible displacement faulting event (year)
c

      min_t1 = 0.0d0
      max_t1 = 10000.0d0

c
c...  Amount of largest credible displacement per faulting event (meter)
c

      min_LDNW = 4.5d-2
      max_LDNW = 25.0d-2

      min_LDNE = 6.0d-2
      max_LDNE = 45.0d-2

c
c...  Largest credible displacement along multiple slip surfaces (meter)
c

      LD_max = 45.0d-2
```

```
c
c... Amount of cumulative displacement rate (meter/year)
c

      min_CDNW = 0.0d-3
      max_CDNW = 0.01d-3

      min_CDNE = 0.00004d-3
      max_CDNE = 0.007d-3

c
c... Threshold Displacement (meter)
c

      min_TD = 0.1d0
      max_TD = 0.5d0
```

[Amitava Ghosh, June 7, 1996]

3. VERIFICATION OF DIFFERENT PARTS OF THE FAULTING MODULE

3.1. Calculation of Intersected Length of a Fault

In this case, the coordinates of two ends of four faults were tested. The faults are shown in Figure 3-1. Four faults were tested: Fault 1 and Fault 2 fall completely within the repository region, in this case Region A. One end of Fault 3 intersects the region (only one end inside the region). Both ends of Fault 4 are outside the region, as shown in Figure 3-1. The coordinates of the both ends of the faults are given below along with the fault length and the length of the fault intersected by the repository region A.

Fault 1:
End 1: [171200, 236200] End 2: [171400, 235600]
Length = 632.456
Intersected Length = 632.456

Fault 2:
End 1: [171300, 235600] End 2: [171300, 235300]
Length = 300.000
Intersected Length = 300.000

Fault 3:
End 1: [170900, 235400] End 2: [171000, 236000]
Length = 608.276
Intersected Length = 103.852

Fault 4:
End 1: [171500, 235200] End 2: [171750, 236000]
Length = 838.153
Intersected Length = 562.013

Figures 3-2 and 3-3 show Fault 3 and Fault 4 and the segments of the region intersected (real intersection) by them. Following are the results from the FAULTING module which shows good agreements with the results.

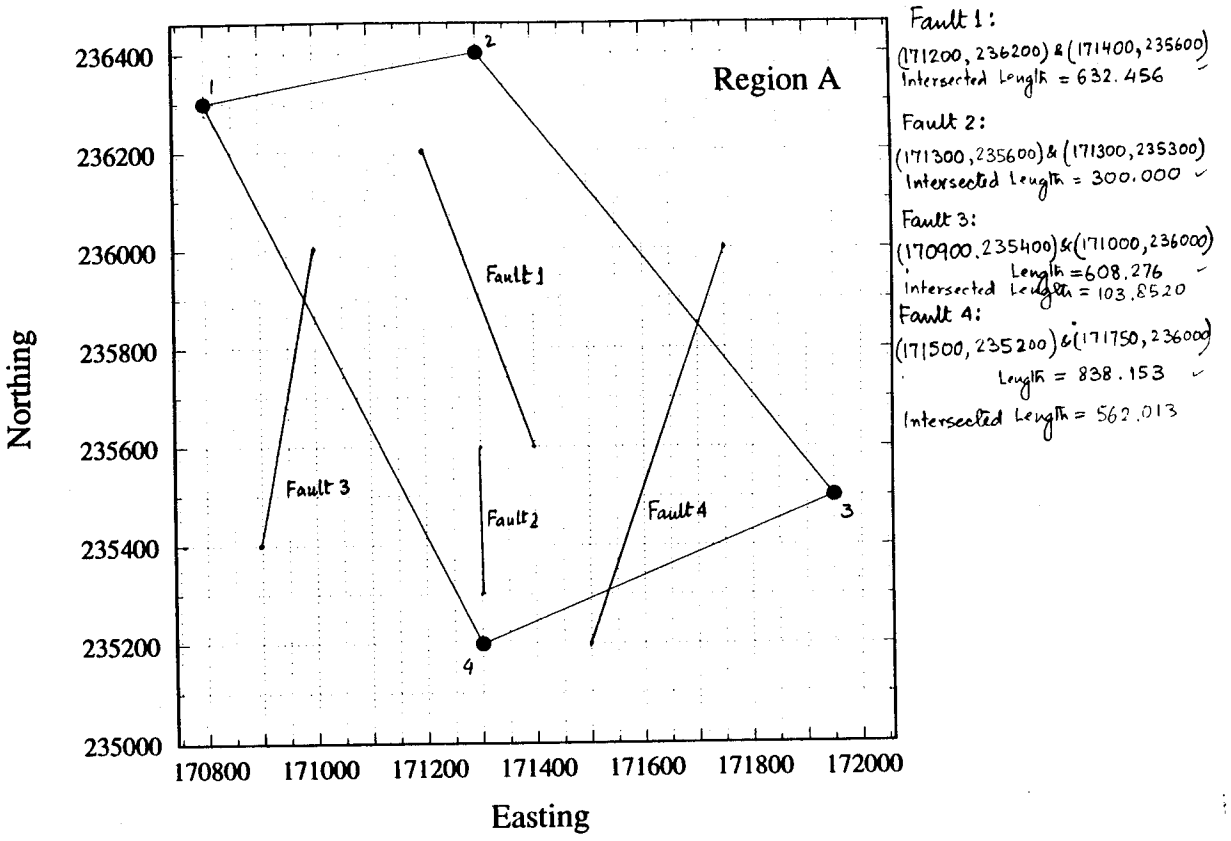


Figure 3-1 Region A with four fault planes used in verification of the code

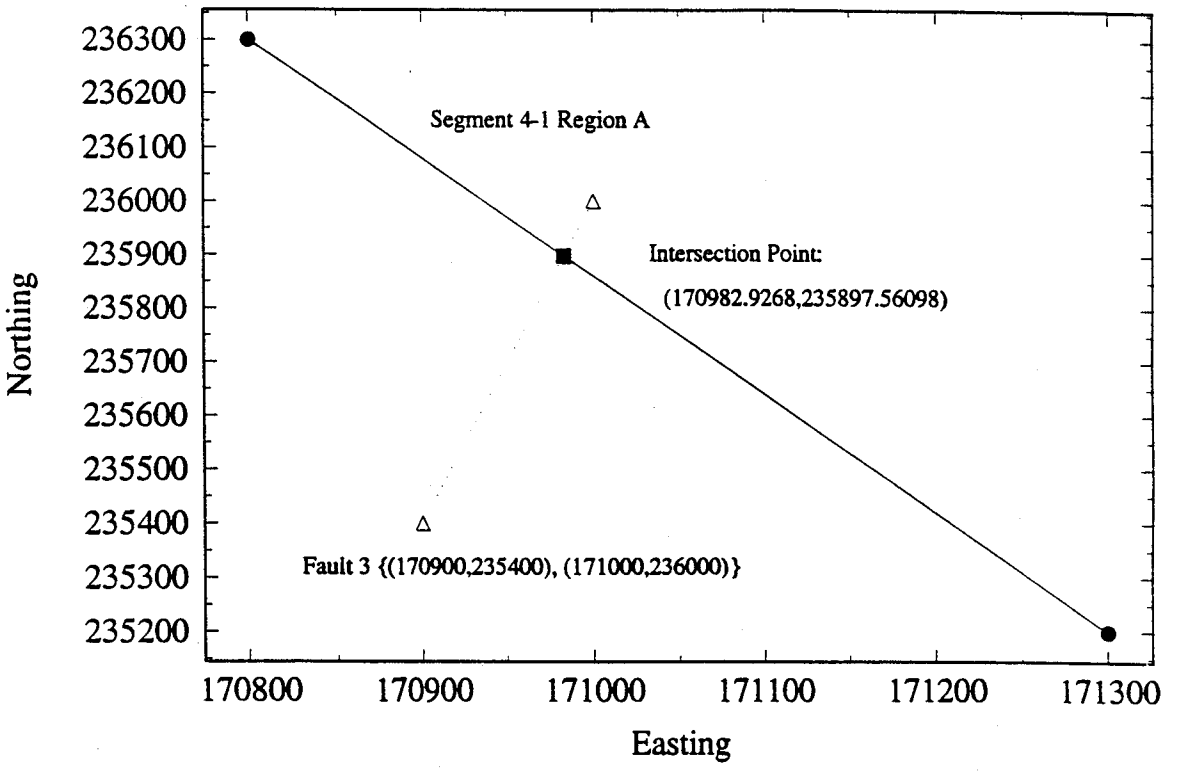


Figure 3-2 Intersection point of Fault 3 and segments of Region A

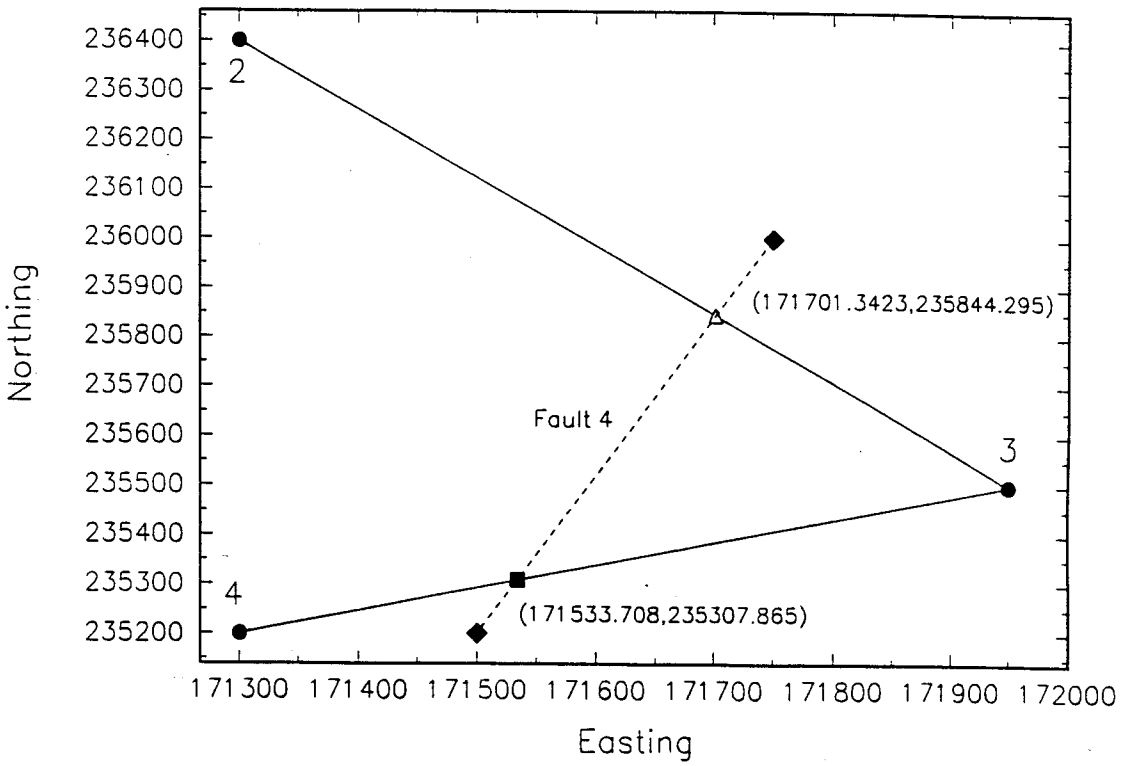


Figure 3-3 Intersection points of Fault 4 and segments of Region A

FAULT 1:

x1 of fault => 171200
y1 of fault => 236200
x2 of fault => 171400
y2 of fault => 235600
Region (PU,PL,A,B,C,D) => A

... Fault Plane ...
End 1: x = 171200.00000000 y = 236200.00000000
End 2: x = 171400.00000000 y = 235600.00000000
Region: A

x(1) = 170800.0 y(1) = 236300.0
x(2) = 171300.0 y(2) = 236400.0
x(3) = 171950.0 y(3) = 235500.0
x(4) = 171300.0 y(4) = 235200.0
x(5) = 170800.0 y(5) = 236300.0

171200.00000000 236200.00000000 falls inside the region
171400.00000000 235600.00000000 falls inside the region

Intersection Points:
Point 1: 171200.00000000 236200.00000000
Point 2: 171400.00000000 235600.00000000
Intersected length = 632.45553203368

Another run => y

FAULT 2:

x1 of fault => 171300
y1 of fault => 235600
x2 of fault => 171300
y2 of fault => 235300
Region (PU,PL,A,B,C,D) => A

... Fault Plane ...
End 1: x = 171300.00000000 y = 235600.00000000
End 2: x = 171300.00000000 y = 235300.00000000
Region: A

x(1) = 170800.0 y(1) = 236300.0
x(2) = 171300.0 y(2) = 236400.0
x(3) = 171950.0 y(3) = 235500.0
x(4) = 171300.0 y(4) = 235200.0
x(5) = 170800.0 y(5) = 236300.0

171300.00000000 235600.00000000 falls inside the region
171300.00000000 235300.00000000 falls inside the region

Intersection Points:
Point 1: 171300.00000000 235600.00000000
Point 2: 171300.00000000 235300.00000000
Intersected length = 300.00000000000

Another run => y

FAULT 3:

x1 of fault => 170900
y1 of fault => 235400
x2 of fault => 171000
y2 of fault => 236000
Region (PU,PL,A,B,C,D) => A

... Fault Plane ...
End 1: x = 170900.00000000 y = 235400.00000000
End 2: x = 171000.00000000 y = 236000.00000000
Region: A

x(1) = 170800.0 y(1) = 236300.0
x(2) = 171300.0 y(2) = 236400.0
x(3) = 171950.0 y(3) = 235500.0
x(4) = 171300.0 y(4) = 235200.0
x(5) = 170800.0 y(5) = 236300.0

170900.00000000 235400.00000000 falls outside the region
171000.00000000 236000.00000000 falls inside the region

In subroutine Intersection
x1 = 170800.00000000 y1 = 236300.00000000
x2 = 171300.00000000 y2 = 236400.00000000
x3 = 170900.00000000 y3 = 235400.00000000

x4 = 171000.00000000 y4 = 236000.00000000
Part 1 = -16078881000000. Part 2 = 16128488000000.
Part 4 = -27817218000000. Part 5 = 27885760000000.
Part 6 = -10000.0000000000 Part 7 = 300000.00000000
xi = 171058.62068966 yi = 236351.72413793

Subroutine Inlength
Data about Intersection:
Segment: 1
x1 = 170800.00000000 y1 = 236300.00000000
x2 = 171300.00000000 y2 = 236400.00000000
Intersection Point:
xi = 171058.62068966 yi = 236351.72413793
A = 356.57573453473 B = 964.85198756455 C = 246.15956272518
D = 263.74238863410 E = 509.90195135928 F = 608.27625302982

In subroutine Intersection
x1 = 171300.00000000 y1 = 236400.00000000
x2 = 171950.00000000 y2 = 235500.00000000
x3 = 170900.00000000 y3 = 235400.00000000
x4 = 171000.00000000 y4 = 236000.00000000
Part 1 = -22099812000000. Part 2 = 22181945000000.
Part 4 = -36235122000000. Part 5 = 36348720000000.
Part 6 = 90000.000000000 Part 7 = 390000.00000000
xi = 171110.41666667 yi = 236662.50000000

Subroutine Inlength
Data about Intersection:
Segment: 2
x1 = 171300.00000000 y1 = 236400.00000000
x2 = 171950.00000000 y2 = 235500.00000000
Intersection Point:
xi = 171110.41666667 yi = 236662.50000000
A = 671.63836272043 B = 1279.9146157502 C = 1433.9827138467
D = 323.80254828797 E = 1110.1801655587 F = 608.27625302982

In subroutine Intersection
x1 = 171950.00000000 y1 = 235500.00000000
x2 = 171300.00000000 y2 = 235200.00000000
x3 = 170900.00000000 y3 = 235400.00000000
x4 = 171000.00000000 y4 = 236000.00000000
Part 1 = 30198825000000. Part 2 = -30260324000000.

Part 4 = 35966766000000. Part 5 = -36051360000000.
Part 6 = 30000.000000000 Part 7 = -390000.00000000
xi = 170830.55555556 yi = 234983.33333333

Subroutine Inlength
Data about Intersection:
Segment: 3
x1 = 171950.00000000 y1 = 235500.00000000
x2 = 171300.00000000 y2 = 235200.00000000
Intersection Point:
xi = 170830.55555556 yi = 234983.33333333
A = 1030.6903176339 B = 422.41406460403 C = 517.03242728497
D = 1232.9234804488 E = 715.89105316382 F = 608.27625302982

In subroutine Intersection
x1 = 171300.00000000 y1 = 235200.00000000
x2 = 170800.00000000 y2 = 236300.00000000
x3 = 170900.00000000 y3 = 235400.00000000
x4 = 171000.00000000 y4 = 236000.00000000
Part 1 = 24143916000000. Part 2 = -24214019000000.
Part 4 = 27760722000000. Part 5 = -27857440000000.
Part 6 = -110000.00000000 Part 7 = -300000.00000000
xi = 170982.92682927 yi = 235897.56097561

Subroutine Inlength
Data about Intersection:
Segment: 4
x1 = 171300.00000000 y1 = 235200.00000000
x2 = 170800.00000000 y2 = 236300.00000000
Intersection Point:
xi = 170982.92682927 yi = 235897.56097561
A = 103.852043200217 B = 504.42420982961 C = 442.06265757053
D = 766.24193978893 E = 1208.3045973595 F = 608.27625302982
Intersection is real

k = 2 xin(k) = 170982.92682927 yin(k) = 235897.56097561

Intersection Points (In subroutine segment):
Point 1: 171000.00000000 236000.00000000
Point 2: 170982.92682927 235897.56097561
Intersection Points:
Point 1: 171000.00000000 236000.00000000

Point 2: 170982.92682927 235897.56097561

Intersected length = 103.852043200217

Another run => y

FAULT 4:

x1 of fault => 171500
y1 of fault => 235200
x2 of fault => 171750
y2 of fault => 236000
Region (PU,PL,A,B,C,D) => A

... Fault Plane ...
End 1: x = 171500.00000000 y = 235200.00000000
End 2: x = 171750.00000000 y = 236000.00000000
Region: A

x(1) = 170800.0 y(1) = 236300.0
x(2) = 171300.0 y(2) = 236400.0
x(3) = 171950.0 y(3) = 235500.0
x(4) = 171300.0 y(4) = 235200.0
x(5) = 170800.0 y(5) = 236300.0

171500.00000000 235200.00000000 falls outside the region
171750.00000000 236000.00000000 falls outside the region

In subroutine Intersection
x1 = 170800.00000000 y1 = 236300.00000000
x2 = 171300.00000000 y2 = 236400.00000000
x3 = 171500.00000000 y3 = 235200.00000000
x4 = 171750.00000000 y4 = 236000.00000000
Part 1 = -10078252500000.0 Part 2 = 10142720000000.0
Part 4 = -27811224000000. Part 5 = 27899920000000.
Part 6 = -25000.000000000 Part 7 = 400000.00000000
xi = 171913.33333333 yi = 236522.66666667

Subroutine Inlength
Data about Intersection:
Segment: 1
x1 = 170800.00000000 y1 = 236300.00000000

x2 = 171300.00000000 y2 = 236400.00000000
Intersection Point:
xi = 171913.33333333 yi = 236522.66666667
A = 547.59311739851 B = 1385.7458481105 C = 625.47972700072
D = 1135.3816783600 E = 509.90195135928 F = 838.15273071201

In subroutine Intersection
x1 = 171300.00000000 y1 = 236400.00000000
x2 = 171950.00000000 y2 = 235500.00000000
x3 = 171500.00000000 y3 = 235200.00000000
x4 = 171750.00000000 y4 = 236000.00000000
Part 1 = -16094895000000. Part 2 = 16222812500000.
Part 4 = -36045576000000. Part 5 = 36221280000000.
Part 6 = 225000.00000000 Part 7 = 520000.00000000
xi = 171701.34228188 yi = 235844.29530201

Subroutine Inlength
Data about Intersection:
Segment: 2
x1 = 171300.00000000 y1 = 236400.00000000
x2 = 171950.00000000 y2 = 235500.00000000
Intersection Point:
xi = 171701.34228188 yi = 235844.29530201
A = 163.13039725267 B = 675.02233345934 C = 424.69979487818
D = 685.48037068055 E = 1110.1801655587 F = 838.15273071201
Intersection is real

k = 1 xin(k) = 171701.34228188 yin(k) = 235844.29530201

In subroutine Intersection
x1 = 171950.00000000 y1 = 235500.00000000
x2 = 171300.00000000 y2 = 235200.00000000
x3 = 171500.00000000 y3 = 235200.00000000
x4 = 171750.00000000 y4 = 236000.00000000
Part 1 = 36342427500000. Part 2 = -36418760000000.
Part 4 = 35989128000000. Part 5 = -36093840000000.
Part 6 = 75000.000000000 Part 7 = -520000.00000000
xi = 171533.70786517 yi = 235307.86516854

Subroutine Inlength
Data about Intersection:
Segment: 3

x1 = 171950.00000000 y1 = 235500.00000000
x2 = 171300.00000000 y2 = 235200.00000000
Intersection Point:
xi = 171533.70786517 yi = 235307.86516854
A = 725.14337376209 B = 113.00935694992 C = 257.39903035103
D = 458.49202281278 E = 715.89105316382 F = 838.15273071201
Intersection is real

k = 2 xin(k) = 171533.70786517 yin(k) = 235307.86516854

In subroutine Intersection
x1 = 171300.00000000 y1 = 235200.00000000
x2 = 170800.00000000 y2 = 236300.00000000
x3 = 171500.00000000 y3 = 235200.00000000
x4 = 171750.00000000 y4 = 236000.00000000
Part 1 = 30240840000000. Part 2 = -30356547500000.
Part 4 = 27543096000000. Part 5 = -27701680000000.
Part 6 = -275000.00000000 Part 7 = -400000.00000000
xi = 171418.51851852 yi = 234939.25925926

Subroutine Inlength
Data about Intersection:
Segment: 4
x1 = 171300.00000000 y1 = 235200.00000000
x2 = 170800.00000000 y2 = 236300.00000000
Intersection Point:
xi = 171418.51851852 yi = 234939.25925926
A = 1111.3284355367 B = 273.17570482465 C = 1494.7175389558
D = 286.41294159630 E = 1208.3045973595 F = 838.15273071201
Intersection Points:
Point 1: 171701.34228188 235844.29530201
Point 2: 171533.70786517 235307.86516854

Intersected length = 562.01297650942

Another run => n

[Amitava Ghosh, June 7, 1996]

3.2. Simulation of Uniformly Distributed Random Numbers Between [0,1]

Uniformly distributed random numbers between 0 and 1 are simulated using the *drand(k)* function of SUNf77 compiler where k>0 starts a new sequence of random numbers and k = 0 gives the next random number in the sequence. *drand(k)* function gives the double precision random numbers.

Using these random numbers, a set of random numbers uniformly distributed between [a,b] can be generated from

$$y = (b - a)\, x + a$$

where,
x = uniform random number between [0,1]
y = uniform random number between [a,b].

A subroutine to generate uniformly distributed random numbers between [0,1], called *random*, is left in the file *fault.f* although it was not used to generate the uniformly distributed random numbers. This subroutine may be used in place of the *drand(k)* function with some modifications of the procedure for calling for the random number in *fault.f* as this subroutine requires the previous random number as seed for generation for next random number.

[Amitava Ghosh, June 27, 1996]

3.3. Simulation of Normally Distributed Random Numbers

A subroutine *gauss* has been developed following the mathematical guideline given in Section 2.1.4 and adopting the routine given in Ghosh and Kulatilake (1987). A set of 500 normally distributed random numbers with a probability 90% falling between [-1, 1] was generated. The statistics of the generated numbers are given below:

	Input Data	**Normal(3.74e-3,0.59)**
Minimum	-1.584767	
Maximum	1.966892	
Mode	-0.128587	3.743165e-3
Mean	3.743165e-3	3.743165e-3
Std Deviation	0.586337	0.586337
Variance	0.343791	0.343791
Skewness	0.119546	0.0
Kurtosis	3.05641	3.0

Best Fit Results	
C-S Test	57.136959
K-S Test	0.023695
A-D Test	0.231722

Figure 3-4 shows the histogram of random numbers with a fitted normal distribution with mean and standard deviation equal to 0.0037 and 0.5863 respectively. They compare very well with the population mean and standard deviation equal to 0.0 and 0.6079 respectively. The skewness and kurtosis of the data set indicate normality. Figure 3-5 shows the cumulative distribution of these numbers. The numbers were tested for normality. The data set passes Kolmogorov-Smirnov (K-S) test for goodness-of-fit with α = 0.05. As expected, with a larger set of random numbers, the sample mean and standard deviation become closer to the population mean and standard deviation. This has been tested with different data sets. For example, when the number of generated random numbers is 1000, the sample mean and standard deviation are 0.0012 and 0.5987 respectively, as shown below. The skewness and kurtosis of the data set have improved quite a bit.

	Input Data	**Normal(1.25e-3,0.60)**
Minimum	-2.051897	
Maximum	1.859709	
Mode	-0.056978	1.249021e-3
Mean	1.249021e-3	1.249021e-3
Std Deviation	0.598718	0.598718
Variance	0.358463	0.358463
Skewness	-0.012203	0.0
Kurtosis	2.969442	3.0

Best Fit Results	
C-S Test	37.568098
K-S Test	8.731377e-3
A-D Test	0.077632

[Amitava Ghosh, June 28, 1996]

3.4. Simulation of Beta Distributed Random Numbers

A subroutine *betad* has been developed following the mathematical guideline given in Section 2.1.5 with any acceptable values of α and β. In the file *fault.inc*, the values of α and β are fixed as 1.5 and 3.0, as given in Stirewalt et al. (1995). A set of 1000 random numbers between [0, 1] was generated. Sample statistics show that sample α and β are 1.50 and 3.11 respectively. Sample mean and variance are 0.3279 and 0.0390 respectively which compare very well with population mean of 0.3333 and population variance of 0.0404. Figure 3-6 shows the histogram of random numbers with beat distribution fitted over it.

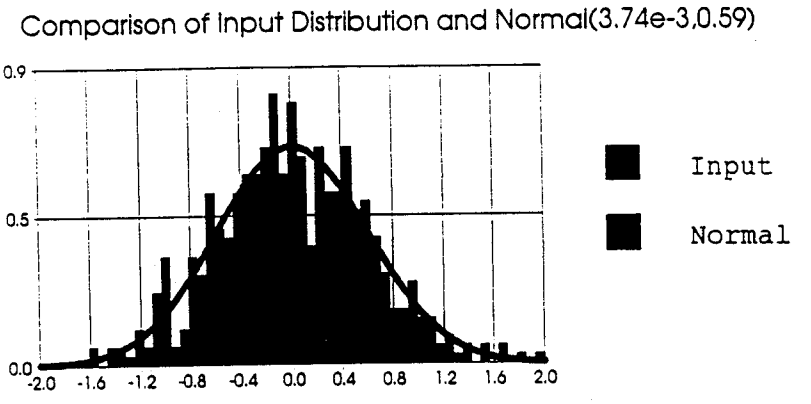


Figure 3-4 Histogram of random numbers, generated by *gauss*, having normal distribution

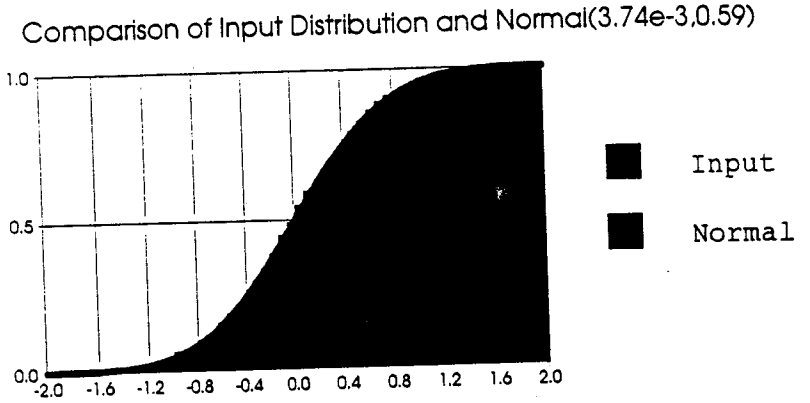
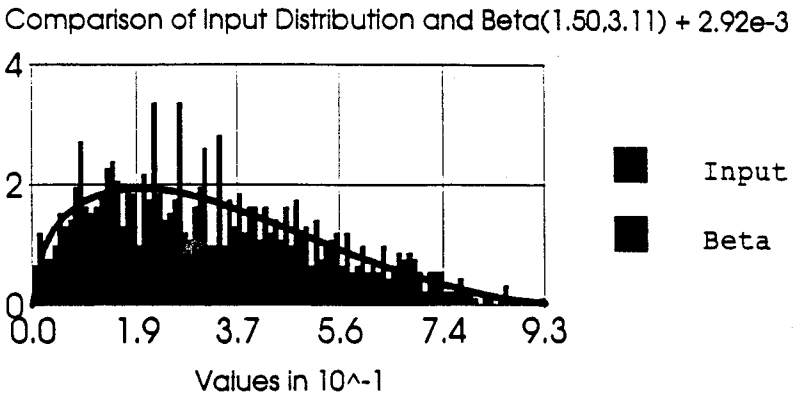


Figure 3-5 Cumulative distribution of random numbers generated by *gauss* having normal distribtuion



No. of data points = 1000

Figure 3-6 Histogram of random numbers generated by *betad* having beta distribution

	Input Data	Beta(1.50,3.11) + 2.92e-3
Minimum	2.91705e-3	
Maximum	0.92994	
Mode	0.206862	0.191073
Mean	0.327924	0.325007
Std Deviation	0.197694	0.197694
Variance	0.039083	0.039083
Skewness	0.485402	0.535402
Kurtosis	2.421904	3.38095

Best Fit Results

C-S Test	13.767742
K-S Test	0.013351
A-D Test	0.258163

[Amitava Ghosh, June 28, 1996]

4. OTHER FEATURES

4.1. Date and Time Stamp

This code will write the date and time of running on the output file. It uses the *fdate()* function from the SUNf77 library.

[Amitava Ghosh, June 27, 1996]

4.2. File for Plotting the Faults and the Repository Region

At present, CNWRA does not have any software which can plot the faults and the repository while the module is running. Only available software is a freeware called PLOTMTV which does a decent job in plotting the faults from a data file. It requires the data in a certain format with several lines of header information for formatting and manipulating the visual look of the plot. The FAULTING module automatically writes the necessary information to the plotting files for processing by PLOTMTV. In most cases, the plot file will run without any modification on PLOTMTV and produce a decent plot. User may want to change the plot file for enhancement of the plot. PLOTMTV can produce a postscript output for plotting on postscript printer. Present setup in the FAULTING module only produces black and white

output. With trivial modification and proper setting of PLOTMTV program, a color output can be generated.

[Amitava Ghosh, June 27, 1996]

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[Amitava Ghosh, June 28, 1996]

CENTER FOR NUCLEAR WASTE REGULATORY ANALYSES

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Development of the FAULTING

SCIENTIFIC NOTEBOOK
Development of the FAULTING Module

by

Amitava Ghosh

Southwest Research Institute
Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas

January 20, 1997

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1. INITIAL ENTRIES

Scientific NoteBook: # 167

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Project Title: Development of the FAULTING Module of Phase 3 IPA

Project Staff: Amitava Ghosh

By agreement with the CNWRA QA this NoteBook is to be printed at approximate quarterly intervals. This computerized Scientific NoteBook is intended to address the criteria of CNWRA QAP-001.

[Amitava Ghosh, February 28, 1996]

1.1. Objectives

The objective of this activity is to develop the FORTRAN coding of the faulting consequence (FAULTING) module for the Phase 3 of the Nuclear Regulatory Commission (NRC) Iterative Performance Assessment (IPA) activity. The basic approach to the FAULTING module has been described in Stirewalt et al. (1995). Taking into account the published data for faults at Yucca Mountain area, this module provides a framework for determining if the primary fault displacement (that is, displacement along the main fault trace rather than along associated secondary fractures) in the repository block could induce waste package disruption, the timing of that disruption, and the number of waste packages disrupted.
[Amitava Ghosh, February 28, 1996]

1.2. Technical Approaches

The codes for the FAULTING module will be written in Fortran 77. Fault displacement is generated in the FAULTING module along an assumed, unknown, and randomly located fault zone inside the simulation area. These unknown fault zones include those not distinguished or adequately characterized, as well as new faults which may develop during the 10,000 year regulatory time frame of interest. Strike direction is determined as either northeast or northwest observed in the field at and near Yucca Mountain. Whether the fault intersects the potential repository depends on location and orientation of the fault in the simulation area and total fault trace length. Whether waste packages are disrupted is dependent upon amount of displacement exceeding a threshold value which is governed by repository and waste package design and waste package emplacement geometry. If the threshold displacement is exceeded by either

largest credible displacement in a single event or by smaller cumulative displacements with time through multiple events, then number and locations of waste packages intersected and disrupted can be calculated based on length of intersection of the fault zone with the repository, repository design, and waste package emplacement geometry. Location, trace orientation, geometry, activity, number and time and amount of largest credible displacement faulting events, and amount and time of cumulative displacements are chosen randomly from range of published data represented as probability distribution functions (PDFs). It is assumed that the unknown fault zones can possess attributes similar to those of the Ghost Dance and Sundance faults. The fault zone is assigned a randomly selected width, and displacement in the zone is considered along both single and multiple slip surfaces. It is assumed that the variation in dip of the fault has little influence on number of waste packages disrupted, considering horizontal emplacement. If waste package disruption occurs as a result of either a largest credible displacement event or cumulative displacement, the timing of that disruption is relayed to the SOurce TErm Code (SOTEC) for calculation of radionuclide release.

The random numbers following a particular PDF will be generated primarily using the program LHS94 (version 1.1) (Iman and Shortencarier, 1984) which uses the Latin Hypercube method. However, using the LHS94 program is a two step process. All the random numbers needed to run the FAULTING modules should be known beforehand and need to generated in advance of running the module. The final version of the FAULTING module will have an user interface to do this. Additionally, each subroutine of the FAULTING module may use own random number generation routines during development. Currently, the LHS94 code is not under the code configuration management of CNWRA.

[Amitava Ghosh, February 28, 1996]

The code in the present form has own subroutines to generate necessary random numbers from a given distribution. Therefore, at this point, there is no need to generate the random numbers using the LHS routines before the run and use them while running this module. At present, this is quite a cumbersome process as we have to estimate beforehand how many random numbers from each specific distribution is needed. It may also be extremely difficult to guess beforehand as the number of random numbers needed for any simulation drastically goes down if the generated fault does not intersect the given repository region.

[Amitava Ghosh, June 27, 1996]

It was also decided to carry out the complete calculation in double precision. The reason is as follows. In the calculation done by this module, we are dealing with very large numbers (coordinates of the faults) and very small numbers (slipping rate on a fault surface). In both cases, it becomes necessary to keep enough precision in the calculations (at least more than 6 significant digits) so that rounding off error does not mislead the calculation sequence.

[Amitava Ghosh, June 27, 1996]

1.3. Computers, Computer Codes, and Data Files

Table 1-1. Computer, operating system, and compiler to be used in developing FAULTING module

Machine Name	Machine Type	Operating System	Compiler	Location
snowwhite	SUN SPARCstation 20	SUNOS 4.1	f77 (SUN)	Building 189

[Amitava Ghosh, February 28, 1996]

1.4. Mathematical Theory

Not Applicable

[Amitava Ghosh, February 28, 1996]

Two modifications of the algorithm given in Stirewalt et al. (1995) were carried out in this period:

1. Flow chart for calculation of largest credible displacement along single and multiple slip surfaces given in Stirewalt et al. (1995) has been modified to (i) reduce unnecessary calculations, and (ii) carry out the sequence of calculations in a more logical way.

Previously, after randomly generating the largest credible displacement, this amount of displacement was partitioned among 2 to 4 randomly generated slip surfaces of the same fault plane. Thereafter, the slip along each of the multiple surfaces was compared against the threshold value. If failure occurs on any of the multiple slip surfaces of the fault plane, the check for slippage on the fault plane itself. This procedure has been modified to allow the flow of calculation in a more logical way and to eliminate unnecessary calculations.

In the present procedure, once the largest credible displacement is randomly generated for a given fault plane, the displacement is compared with the threshold displacement TD for waste packages, based on a uniform pdf varying between 0.1 and 0.5 m. If only failure is indicated, the total displacement on this fault plane is partitioned among 2 to 4 slip surfaces generated randomly. Displacement on each of these slip surfaces is compared with the threshold displacement TD.

New flow chart is given in Figure 1-1. The code necessary to determine the number of waste packages being disrupted due to the faulting event is under development.

[Amitava Ghosh, August 18, 1996]

2. Previously, comparison of displacement along any of the slip surfaces was carried out against LDmax, which was set to 0.045 m. This is not correct as the correct comparison should be against the threshold displacement for waste package rupture, TD. The code has been modified to reflect this.

[Amitava Ghosh, August 18, 1996]

Algorithm to calculate fault displacement along multiple surfaces has been changed again after consultation with Drs. John Stamatokos and D. Ferrill. In the present algorithm, calculation for single and multiple surfaces are carried out independent of each other. Number of slip surfaces is simulated at the time of generating the fault geometrical parameters.

[Amitava Ghosh, November 15, 1996]

Previously, the threshold displacement for waste package disruption was a random variable varying uniformly between 0.1 m and 0.5 m. After discussion with Dr. B. Sagar, this has been changed to a user-specified variable. At the beginning of the simulation, user is asked interactively to input a specific value for this variable.

[Amitava Ghosh, November 20, 1996]

The new flow chart is given in Figure 1-2.

[Amitava Ghosh, January 28, 1997]

1.5. Assumptions

The assumptions for each of the parameters and the complete module are given in Stirewalt et al. (1995). [Amitava Ghosh, February 28, 1996]

1.6. Initial/Boundary Conditions

Not Applicable [Amitava Ghosh, February 28, 1996]

2. DEVELOPMENT OF THE FAULTING MODULE

2.1. Mathematical Theory

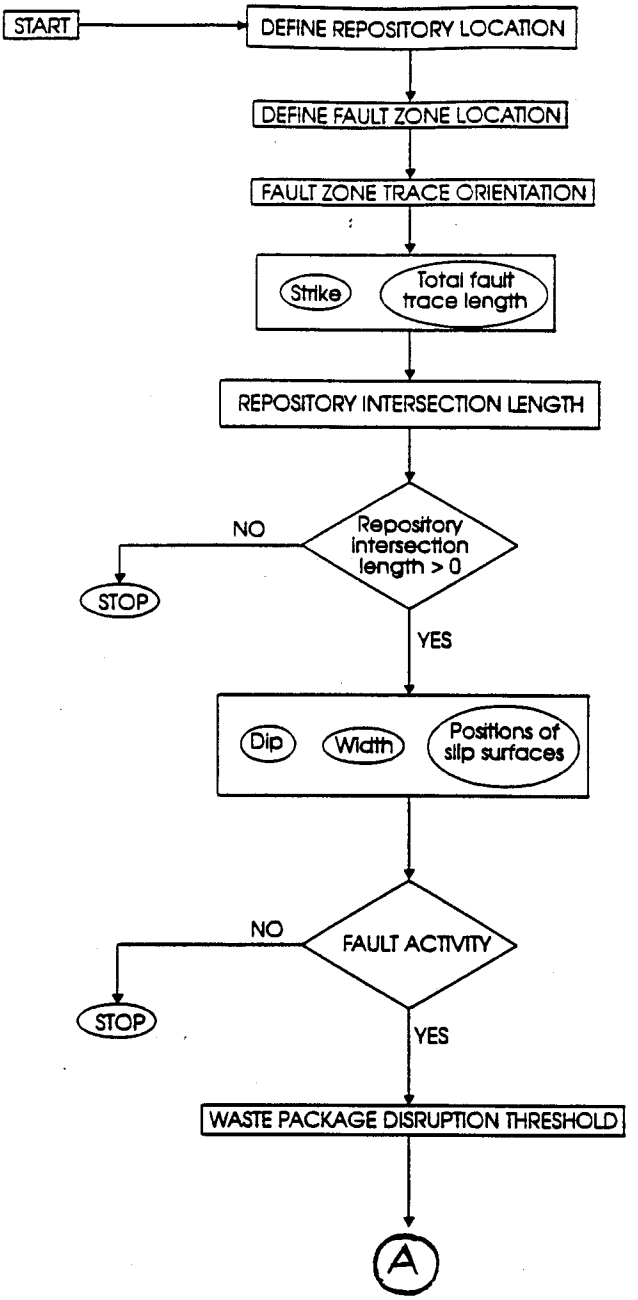

Figure 1-1. Flow diagram illustrating sequential steps for describing faulting events

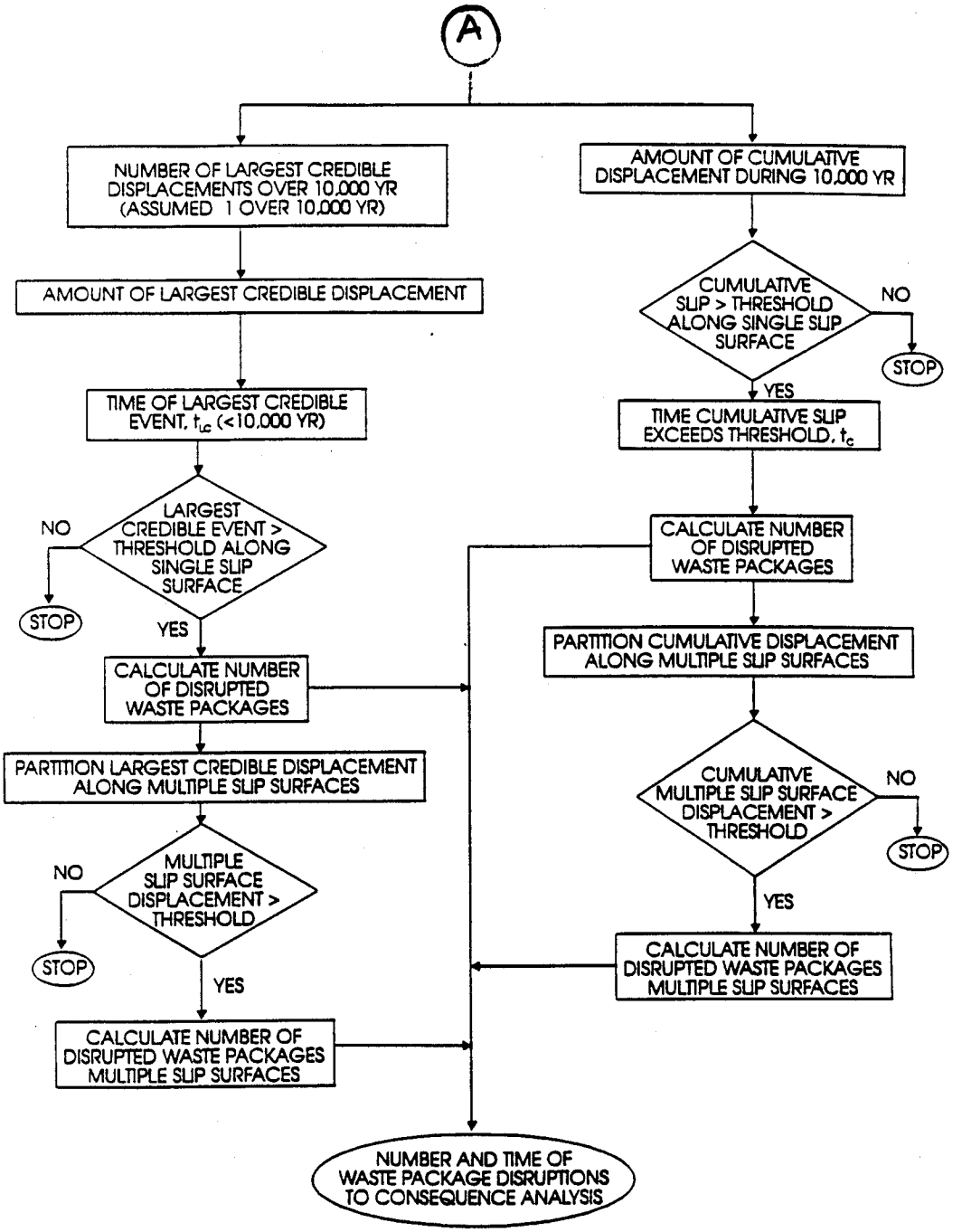

Figure 1-1. Flow diagram illustrating sequential steps for describing faulting events (cont.)

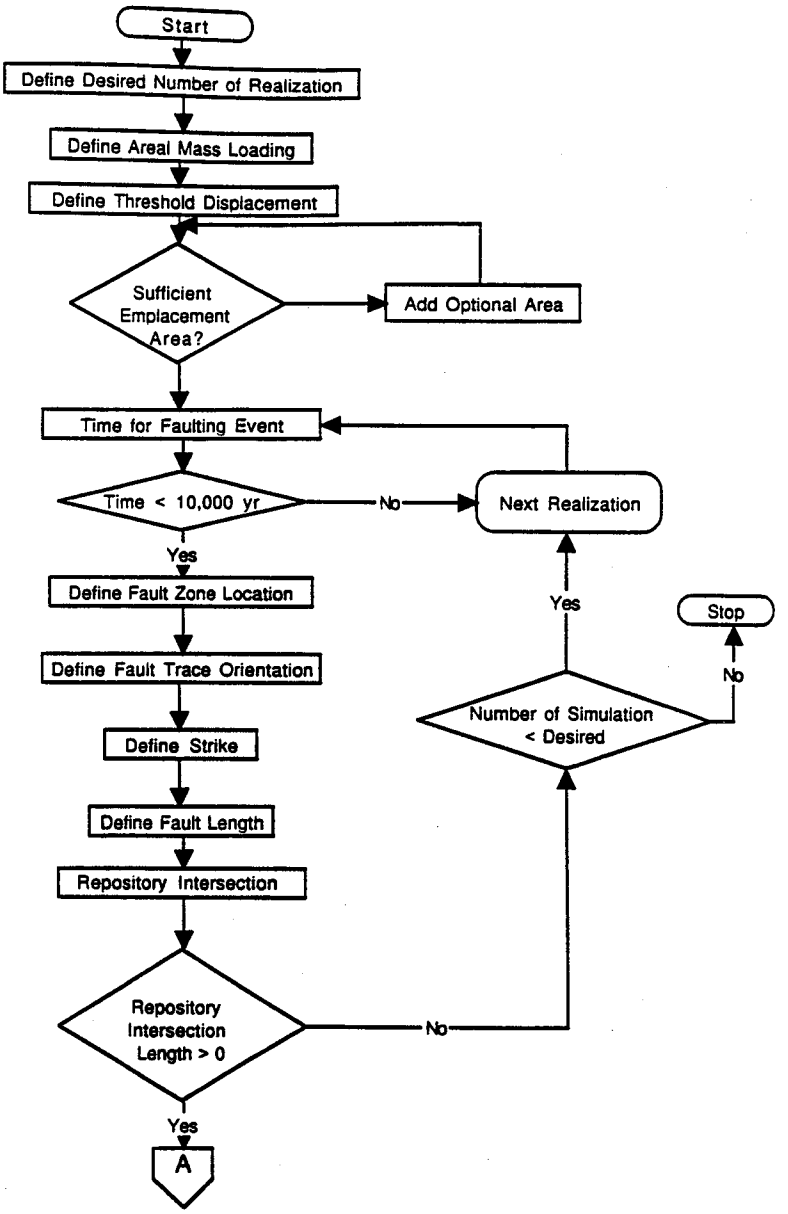

Figure 1-2. Flow diagram illustrating sequential steps for describing faulting events (revised)

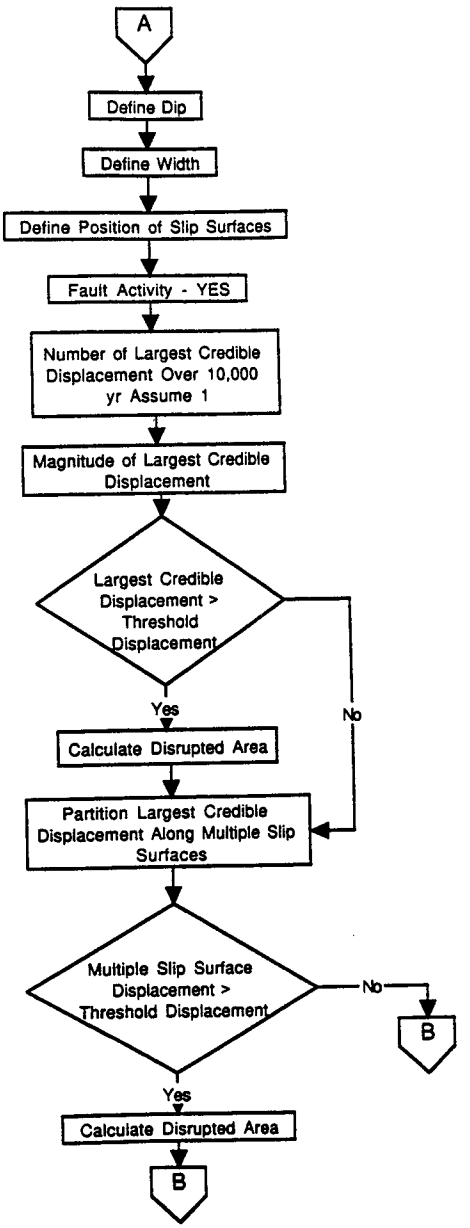

Figure 1-2. Flow diagram illustrating sequential steps for describing faulting events (revised) (cont.)

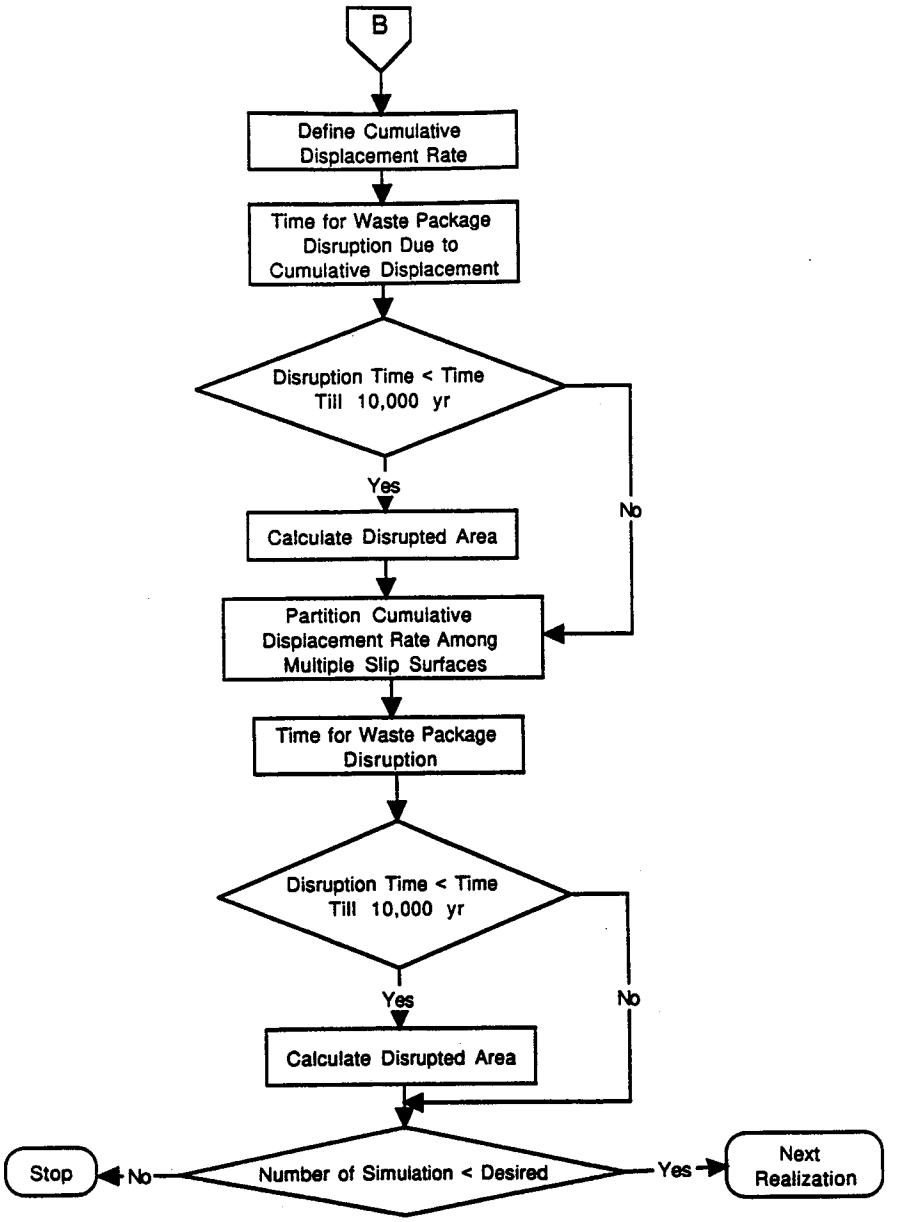

Figure 1-2. Flow diagram illustrating sequential steps for describing faulting events (revised) (cont.)

2.1.1. Coordinates of the Point of Intersection of Two Straight Lines Defined by the Coordinates of the End Points

Line 1: End points are (x_1,y_1) and (x_2,y_2)
Line 1: End points are (x_3,y_3) and (x_4,y_4)
Intersection point: (x_i,y_i)

Equation of line 1:

$$\frac{y-y_1}{x-x_1}=\frac{y_2-y_1}{x_2-x_1} \tag{1}$$

It goes through (x_i,y_i). Therefore,

$$\frac{y_i-y_1}{x_i-x_1}=\frac{y_2-y_1}{x_2-x_1} \tag{2}$$

Similarly,

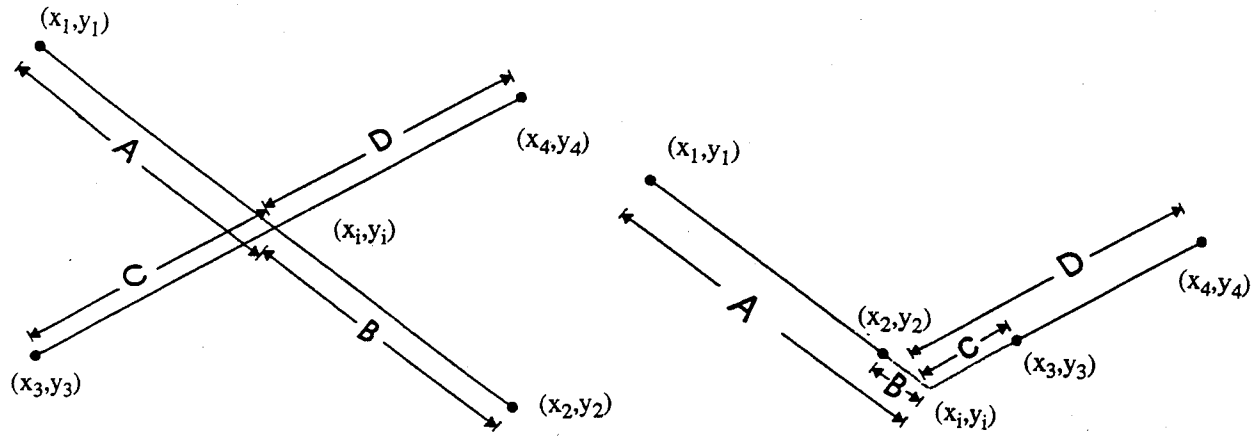

Figure 2-1. Determination of real intersection point of two finite straight lines

$$\frac{y_i - y_3}{x_i - x_3} = \frac{y_4 - y_3}{x_4 - x_3} \tag{3}$$

Solving (2) and (3) for x_i and y_i, we get

$$x_i = \frac{(x_1 - x_2)(x_3 y_4 - x_4 y_3) + (x_3 - x_4)(x_1 y_2 - x_2 y_1)}{-(x_3 y_1 - x_4 y_1 - x_3 y_2 + x_4 y_2 - x_1 y_3 + x_2 y_3 + x_1 y_4 - x_2 y_4)}$$

$$y_i = -\frac{x_2 y_1 y_3 + x_4 y_1 y_3 + x_1 y_2 y_3 - x_4 y_2 y_3 + x_2 y_1 y_4 - x_3 y_1 y_4 - x_1 y_2 y_4 + x_3 y_2 y_4}{-x_3 y_1 + x_4 y_1 + x_3 y_2 - x_4 y_2 + x_1 y_3 - x_2 y_3 - x_1 y_4 + x_2 y_4}$$

These solutions were also verified using the commercial program Mathematica. These equations were coded in the subroutine *intersection.*

These equations do not guarantee that the point of intersection of these lines are real, that is, the point lies on both the lines as shown:

A = length of the line joining (x_1,y_1) and (x_i,y_i)
B = length of the line joining (x_2,y_2) and (x_i,y_i)
C = length of the line joining (x_3,y_3) and (x_i,y_i)
D = length of the line joining (x_4,y_4) and (x_i,y_i)
E = length of the line joining (x_1,y_1) and (x_2,y_2)
F = length of the line joining (x_3,y_3) and (x_4,y_4)

For the intersection to be real, either of the following two conditions needs to be true.

$$A + B = E \Rightarrow (A + B) - E = 0$$

or,

$$C + D = F \Rightarrow (C + D) - F = 0$$

It should be recognized that comparison of real numbers having very similar magnitudes is problematic due to round off errors. Therefore, an acceptable tolerance should be used.

[Amitava Ghosh, March 31, 1996]

The formula for x_i has been changed to be parallel with that of y_i so that the coding of the subroutine becomes easier. The revised formula is as follows:

$$x_i = \frac{-x_2x_4y_3+x_1x_4y_3+x_2x_4y_1-x_2x_3y_1-x_1x_4y_2+x_1x_3y_2+x_2x_3y_4-x_1x_3y_4}{-x_3y_1+x_4y_1+x_3y_2-x_4y_2+x_1y_3-x_2y_3-x_1y_4+x_2y_4}$$

For the intersection to be real, both of the above two conditions needs to be true. Otherwise, in some cases wrong conclusions will be made. This has been corrected in the code.

[Amitava Ghosh, May 23, 1996]

2.1.2. Determination whether a given point falls within a quadrilateral defined by the four corners

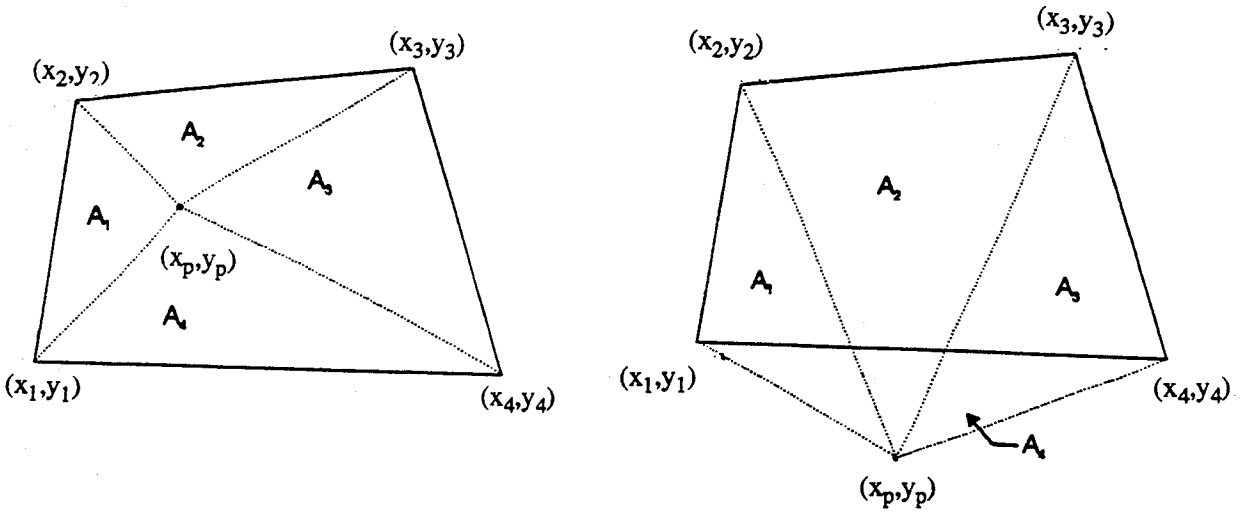

Figure 2-2. Determination whether a given point falls within a given quadrilateral

Given point is (x_p,y_p). The quadrilateral has corners defined by (x_1,y_1), (x_2,y_2), (x_3,y_3), and (x_4,y_4).

A1: area of triangle (x_1,y_1), (x_2,y_2), (x_p,y_p)
A2: area of triangle (x_2,y_2), (x_3,y_3), (x_p,y_p)
A3: area of triangle (x_3,y_3), (x_4,y_4), (x_p,y_p)

A4: area of triangle (x_4,y_4), (x_1,y_1), (x_p,y_p)

Area of quadrilateral (x_1,y_1), (x_2,y_2), (x_3,y_3), (x_4,y_4) = A
= area of [triangle (x_1,y_1), $x_2,y_2)$, (x_3,y_3) + triangle (x_3,y_3), (x_4,y_4) (x_1,y_1)]

If the point (x_p,y_p) is inside the quadrilateral, then

$$A = A_1 + A_2 + A_3 + A_4$$

If outside,

$$A < (A_1 + A_2 + A_3 + A_4)$$

[Amitava Ghosh, March 31, 1996]

2.1.3. Determination of the Fault Length Intersected by the Repository Block

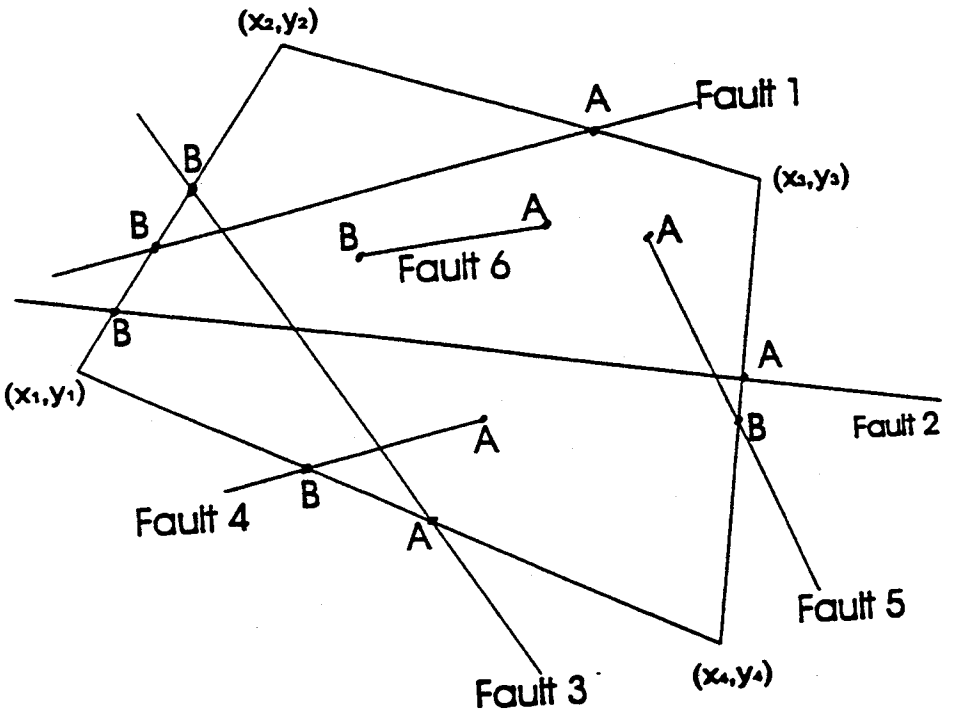

Figure 2-3. Determination of the length of a given fault intersected by a repository block

- Fault 7: Intersection length = Fault length
- Fault 5, Fault 6: Intersection length = AB: need to find only B
- Fault 1, Fault 2, Fault 3, Fault 4: Intersection Length = AB: need to know both A and B

Known: (i) Two ends of each fault (xf_1, yf_1) and (xf_2, yf_2)
(ii) Four corners (x_1,y_1), (x_2,y_2), (x_3,y_3), (x_4,y_4)

Step 1: Determine whether each end of the fault is within the boundary
if yes, intersection length = fault length

Step 2: If one end is within the boundary, determine
(i) which segment it is intersecting
(ii) calculate length AB

Step 3: If both ends are outside the boundary, determine
(i) which segments it is intersecting
(ii) calculate length AB

[Amitava Ghosh, March 31, 1996]

The length of the portion of a randomly generated fault intersected by a given repository region is calculated following the above-mentioned algorithm. Subroutine *checkin* is used to determine whether both ends of the fault fall within the given region. If both ends of the fault are within the given region then the intersected length is the length of the fault. If one end or both ends fall outside the given region, then subroutine *inlength* is called to determine first the intersection point(s) of the fault and the sides of the quadrilateral region. There will be one or two real intersection points depending on whether one or two end points fall outside the region, respectively. The intersected length for the first case is the distance between the real intersection point and the other end point of the fault which falls within the region. The intersected length for the second case is the distance between the two intersection points.

[Amitava Ghosh, June 7, 1996]

2.1.4. Random Numbers Having Normal Distribution with Mean μ and Standard Deviation σ, N (μ, σ_2)

Random numbers have to be generated with mean μ and standard deviation σ so that there is 90 percent probability that the number will fall between A and B.

$$\mu = \frac{A+B}{2}$$

$$P(x \le A) = \frac{100-90}{2}\% = 5\% = 0.05$$
$$P(X \ge B) = 0.05$$
$$P(Z \le 1.645) = 0.05$$

For a standard normal variate Z,
$P(Z \le 1.645) = 0.05$

Standard deviation of the desired truncated normal distribution is $\sigma = \frac{X-\mu}{1.645} = \frac{B-\mu}{1.645} = \frac{B-A}{2.29}$

Generation of normally distributed random numbers is carried out following Ang and Tang (1984):

If U_1 and U_2 are two uncorrelated uniformly distributed random numbers between 0 and 1, then two normally distributed random numbers with mean μ and standard deviation σ are:

$$x_1 = \mu + \sigma\sqrt{-2lnU_1}\,\mathrm{Cos}2\pi U_2$$
$$x_2 = \mu + \sigma\sqrt{-2lnU_1}\,\mathrm{Sin}2\pi U_2$$

[Amitava Ghosh, March 31, 1996]

Standard deviation of the desired truncated normal distribution is $\sigma = \frac{X-\mu}{1.645} = \frac{B-\mu}{1.645} = \frac{B-A}{3.29}$

This is the corrected form of the equation as 2x1.645 is equal to 3.29, not 2.29 as typed.

[Amitava Ghosh, May 21, 1996]

2.1.5. Beta Distribution in the Interval (A, B) with Parameters α and β

Random numbers Y from a general Beta distribution with lower and upper bounds A and B, respectively, may be obtained through

$$Y = \frac{X-A}{B-A}$$

where X is the corresponding random number for the standard Beta distribution

$$\mu_x = \frac{\alpha}{\alpha + \beta}$$

$$\sigma_x = \frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}$$

Therefore, $\mu_y = (B-A)\mu_x + A = \frac{A\beta + B\alpha}{\alpha+\beta}$

$$\sigma_y = (B-A)^2\sigma_x = \frac{(B-A)^2\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}$$

Generation of Beta distributed random numbers is carried out following Ang and Tang (1984):

A random number X with pdf of the standard Beta distribution with shape parameters σ and β can be generated from

$$X = \frac{U_1^{1/\alpha}}{U_1^{1/\alpha} + u_2^{1/\beta}}$$

where U_1 and U_2 are two random numbers having the standard uniform distribution provided $U_1^{1/\alpha} + U_2^{1/\beta} \le 1$.

[Amitava Ghosh, March 31, 1996]

2.1.6. LogBeta Distribution in the Interval (A, B) with Parameters α and β

X is standard beta distributed with mean equal to 0 and standard deviation equal to 1. Then Y has logbeta distribution if

$$Y = e^X$$

which means

$$\ln Y = X$$

has beta distribution. Consequently, the lower and upper limits will be:

$$a^* = \ln a$$

$$b^* = \ln b$$

Now, we have to generate a standard beta distribution with lower and upper limits are a^* and b^* respectively.

Mean of logbeta distribution $\mu = e^{\frac{\alpha}{\alpha+\beta}}$

Variance of logbeta distribution $\alpha = e^{\frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}}$

Given $\alpha = 1.5, \quad \beta = 3.0$

$\mu = e^{\frac{1.5}{4.5}} = 1.3956$

$\sigma = e^{\frac{1.5x3}{4.5^2x(5.5)}} = 1.0412$

Minimum value $= e^0 = 1$

Maximum value $= e^1 = 2.71828$

Therefore, standard Beta x, i.e., within interval (0,1) distribution, when converted to logbeta distribution Y, will be within the interval (1, 2.71828)

$$Y = \frac{x-a}{b-a} = \frac{x-1}{1.71828}$$

Y will be logbeta distributed with interval between (0,1)

If, for example, we want random numbers which is logbeta within interval (A,B), then:

$$Z = Y(B-A)+A$$

$$Z = \frac{x-a}{b-a}\cdot(B-A)+A$$

$$= \frac{(x-a)(B-A)+A(b-A)}{b-a} = \frac{x(B-A)}{b-a} - \frac{a(B-A)}{b-a} + A$$

$$= x\frac{B-A}{b-a} + \frac{-aB+aA+bA-aA}{b-a}$$

$$= x\frac{B-A}{b-a} + \frac{bA-aB}{b-a}$$

[Amitava Ghosh, June 7, 1996]

2.1.7. Representation of Dip Angle

The given definition of dip given in Stirewalt et al. (1995) is quite inconvenient for computer processing. Dip direction and dip angle would have been a better alternative way of expressing the orientation of fault planes. Unfortunately, the data given here do not have correspondence between the strike and dip of a given fault plane. The field observation is restricted to the distribution of fault dip in two dominant fault orientations, namely, northwest (NW) and northeast (NE). For example, a dip of 60W does not belong to the plane with a particular fault with a given strike. Rather the data give the distribution of strike and dip independently.

A scheme has been devised here to express dip without any other information of direction, e.g., NW, NE, or W. As the faults are striking NE or NW, they will dip either to east or west. Therefore, in this scheme, the dip angle is always measured from the East direction. In other words, dip angle 0 degree and dipping towards east is dip 0. Similarly, dip angle 0 degree and dipping towards west is dip 180 degree. A dip angle of 30 degree and dipping east is dip 30 and dipping west is dip 120 degree.

It should be noted here that this scheme is not quite general and will not work if a fault has the strike towards east. In Yucca Mountain region, the fault orientation is either NE or NW. Therefore, this scheme will work without any problem. A better scheme is necessary to make this code more general and applicable to any other region.

[Amitava Ghosh, June 7, 1996]

2.1.8. Exponentially Distributed Random Numbers

Subroutine *exponential* generates a random sample x which is exponentially distributed with the parameter λ. The PDF of exponential distribution is

$$f(x;\lambda) = \lambda e^{-\lambda x} \qquad x \geq 0 \tag{A-33}$$

where λ is a constant. The mean and standard deviation of the exponential distribution are equal to $1/\lambda$.

The exponentially distributed random number, y, is generated using u, a uniformly distributed random number between 0 and 1 (Ang and Tang, 1984):

2.1.9. Determination of Waste Package Disruption

Subroutine *check_disrupt* calculates the consequence of a faulting event. It calculates the number and percentage of waste packages, and area of emplacement area disrupted for each faulting event. Inputs to this subroutine are the length and width of the fault, areal mass loading (MTU/acre), MTU per waste package, number of waste packages in the emplacement region, and the standoff distance. Standoff distance is the distance normal to the fault assumed to be affected by the movement along the fault plane.

2.1.10. SUBROUTINE *sort*

Subroutine *sort* has been adopted from Press et al. (1986). It sorts a real array of a given length into an ascending order using the Heapsort algorithm. The array is replaced by its sorted rearrangement. Details of the algorithm are available in Press et al. (1986)

2.2. Input Data

2.2.1. Simulation and Repository Regions

The FAULTING module requires information about the origin of the simulation area and the boundaries of different repository blocks which are given in terms of the coordinates of the four corners.

The origin of the simulation area was taken as 170500 m East and 233000 m North, which falls in the middle of the primary emplacement area. Different emplacement areas are given by (TRW Environmental Safety Systems Inc., 1995):

Region Primary Upper:
[(170500E, 234800N), (171300E, 234500N), (171100E, 231100N), (169800N, 231500E)]

Region Primary Lower:
[(171600E, 233700N), (172300E, 233300N), (171700E, 232000N), (171500E, 232100N)]

Optional Region A:
[(170800E, 236300N), (171300E, 236400N), (171950E, 235500N), (171300E, 235200N)]

Optional Region B:
[(169000E, 236800N), (169700E, 236500N), (169400E, 234500N), (168500E, 234800N)]

Optional Region C:
[(168300E, 234500N), (168900E, 234200N), (168200E, 232200N), (167600E, 232500N)]

Optional Region D:
[(169200E, 234200N), (169700E, 234000N), (169100E, 231500N), (168200E, 231700N)]

[Amitava Ghosh, March 31, 1996]

Figure 2-4 is from TRW Environmental Safety Systems Inc. (1995) showing the emplacement regions. Figure 2-5 shows the plots of the regions given by the above-listed coordinate points.

[Amitava Ghosh, June 7, 1996]

2.2.2. Development of Parameter File *fault.inc*

This code requires many site-specific values for different parameters. Previously, the values of these parameters were defined inside the code at the appropriate places where they were first defined. This may be helpful to read the code but has potential danger of accidentally modifying the parameters values during some modification of the code. Consequently, all these constants are declared in a separate file called *fault.inc* which is included in this code at the beginning of compilation. Any modification to the parameters can be done independently in the file *fault.inc* without any possibility of modifying any part of the code accidently. The content of the file *fault.inc* is given below:

```
c
c....C*****************************************************************
c     This file contains values of different variables used in the
c     FAULTING module. Any change to the data should be done here
c     so that the program remains unaffected.
c....C*****************************************************************
```

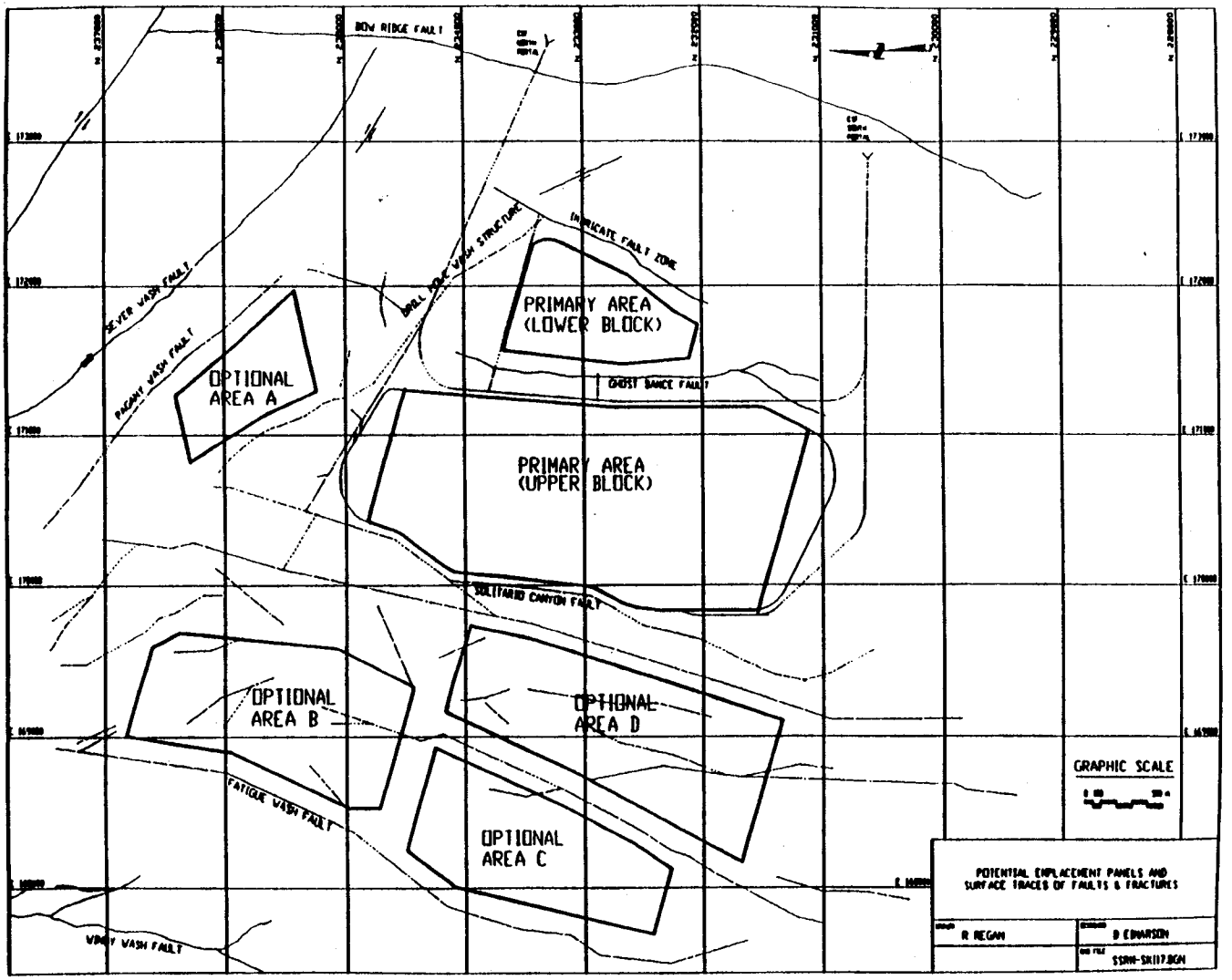

Figure 2-4 Different repository blocks (TRW Environmental Safety Systems Inc., 1995)

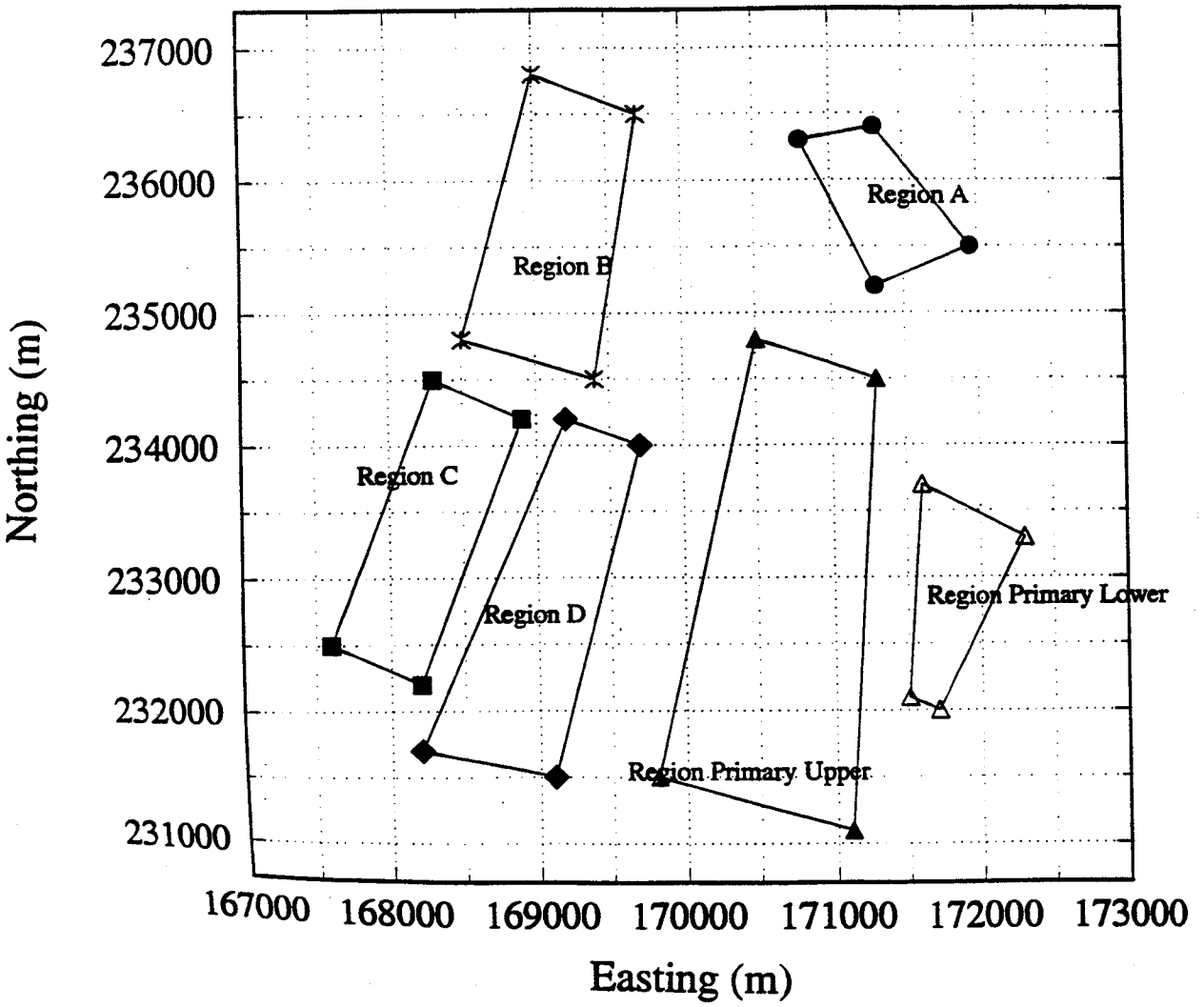

Figure 2-5 Different repository blocks as modeled in the FAULTING module

```
c
c
c
c... Coordinates of the square region (meter)
c
c
c     Define the coordinates of the square region
c     Origin is defined in the middle of the Primary Area (Upper Block)
c     x0 = 170500 East = 170500m, y0 = 233000 North = 233000 m
c     The simulation block is 50km x 50 km centered at (x0,y0)
c

      xleft   = 145500.0
      xright  = 195500.0
      ybottom = 208000.0
      ytop    = 258000.0

c
c...  Probability of fault zone orientation
c

      pforient = 0.25

c
c...  Strike of fault zone (degree, measured from North)
c

      min_SNW = 115.0d0
      max_SNW = 130.0d0

      min_SNE = 65.0d0
      max_SNE = 95.0d0

c
c...  Total trace length (meter)
c

      min_ltNW = 2000.0d0
      max_ltNW = 10000.0d0

      min_ltNE = 3000.0d0
      max_ltNE = 12000.0d0
```

```
c
c... Dip angle (degree, measured from East)
c

      min_thetaNW = 80.0d0
      max_thetaNW = 100.0d0

      min_thetaNE = 90.0d0
      max_thetaNE = 120.0d0

c
c... Fault Width (meter)
c

      min_wNW = 0.5d0
      max_wNW = 275.0d0

      min_wNE = 0.5d0
      max_wNE = 365.0d0

      alpha = 1.5d0
      beta = 3.0d0

c
c... Time of coourance of largest credible displacement faulting event (year)
c

      min_t1 = 0.0d0
      max_t1 = 10000.0d0

c
c... Amount of largest credible displacement per faulting event (meter)
c

      min_LDNW = 4.5d-2
      max_LDNW = 25.0d-2

      min_LDNE = 6.0d-2
      max_LDNE = 45.0d-2

c
c... Largest credible displacement along multiple slip surfaces (meter)
```

```
c

      LD_max = 45.0d-2

c
c...  Amount of cumulative displacement rate (meter/year)
c

      min_CDNW = 0.0d-3
      max_CDNW = 0.01d-3

      min_CDNE = 0.00004d-3
      max_CDNE = 0.007d-3

c
c...  Threshold Displacement (meter)
c

      min_TD = 0.1d0
      max_TD = 0.5d0
```

[Amitava Ghosh, June 7, 1996]

Most of the variables in the include file has been converted to lower case. This was done to comply with the comment of D. Ferrill as SNW for strike for NW direction might be interpreted as South-North-West. New include file is given below:

```
c
c....C*****************************************************************
c       This file contains values of different variables used in the
c       FAULTING module. Any change to the data should be done here
c       so that the program remains unaffected.
c....C*****************************************************************
c

c
c... Coordinates of the square region (meter)
c
c
c       Define the coordinates of the square region
c       Origin is defined in the middle of the Primary Area (Upper Block)
c       x0 = 170500 East = 170500m, y0 = 233000 North = 233000 m
c       The simulation block is 50 km x 50 km centered at (x0,y0)
c

        xleft   = 145500.0
        xright  = 195500.0
```

```
        ybottom = 208000.0
        ytop    = 258000.0

c
c...  Probability of fault zone orientation
c

       pforient = 0.25

c
c...  Strike of fault zone (degree, measured from North)
c

       min_sNW = 115.0d0
       max_sNW = 130.0d0

       min_sNE = 65.0d0
       max_sNE = 95.0d0

c
c...  Total trace length (meter)
c

       min_ltNW = 2000.0d0
       max_ltNW = 10000.0d0

       min_ltNE = 3000.0d0
       max_ltNE = 12000.0d0

c
c...  Dip angle (degree, measured from East)
c

       min_thetaNW = 80.0d0
       max_thetaNW = 100.0d0

       min_thetaNE = 90.0d0
       max_thetaNE = 120.0d0

c
c...  Fault Width (meter)
c

       min_wNW = 0.5d0
       max_wNW = 275.0d0

       min_wNE = 0.5d0
       max_wNE = 365.0d0

       alpha = 1.5d0
       beta = 3.0d0

c
c...  Time of occurrence of largest credible displacement faulting event
(year)
```

```
c     Changed from 0 and 10,000 years to 60,000 and 275,000 years
c
       min_t1 = 60000.0d0
       max_t1 = 275000.0d0

c
c...  Amount of largest credible displacement per faulting event (meter)
c
       min_ldNW = 4.5d-2
       max_ldNW = 25.0d-2

       min_ldNE = 6.0d-2
       max_ldNE = 45.0d-2

c
c...  Largest credible displacement along multiple slip surfaces (meter)
c
       ld_max = 45.0d-2

c
c...  Amount of cumulative displacement rate (meter/year)
c
       min_cdNW = 0.0d-3
       max_cdNW = 0.01d-3

       min_cdNE = 0.00004d-3
       max_cdNE = 0.007d-3

c
c...  Define standoff distance
c
       standoff = 0.0

c
c...  Define MTU per waste package
c
       MTU_wp = 9.0
```

2.2.3. Function *drand_a()*

A new function *drand_a()* is inserted in the code. Function *drand()* of the SUN compiler has been used to generate uniformly distributed random numbers. To make the code portable, function *drand_a()* is inserted as an alternative to the *darnd()* function. This function has been developed from Ripley (1987). Everywhere function *drand()* has been called, the line has to be replaced by the call to *drand_a()*. This function does not take any argument. The seed for random number generation comes through the COMMON statement. Moreover, both *seed* and *drand_a* have to be defined as REAL*8 in each routine

where *drand_a()* will be used. These codes are all there in the code. They have to be uncommented and calls to *darand()* function have to be commented.

3. VERIFICATION OF DIFFERENT PARTS OF THE FAULTING MODULE

3.1. Calculation of Intersected Length of a Fault

In this case, the coordinates of two ends of four faults were tested. The faults are shown in Figure 3-1. Four faults were tested: Fault 1 and Fault 2 fall completely within the repository region, in this case Region A. One end of Fault 3 intersects the region (only one end inside the region). Both ends of Fault 4 are outside the region, as shown in Figure 3-1. The coordinates of the both ends of the faults are given below along with the fault length and the length of the fault intersected by the repository region A.

Fault 1:
End 1: [171200, 236200] End 2: [171400, 235600]
Length = 632.456
Intersected Length = 632.456

Fault 2:
End 1: [171300, 235600] End 2: [171300, 235300]
Length = 300.000
Intersected Length = 300.000

Fault 3:
End 1: [170900, 235400] End 2: [171000, 236000]
Length = 608.276
Intersected Length = 103.852

Fault 4:
End 1: [171500, 235200] End 2: [171750, 236000]
Length = 838.153
Intersected Length = 562.013

Figures 3-2 and 3-3 show Fault 3 and Fault 4 and the segments of the region intersected (real intersection) by them. Following are the results from the FAULTING module which shows good agreements with the results.

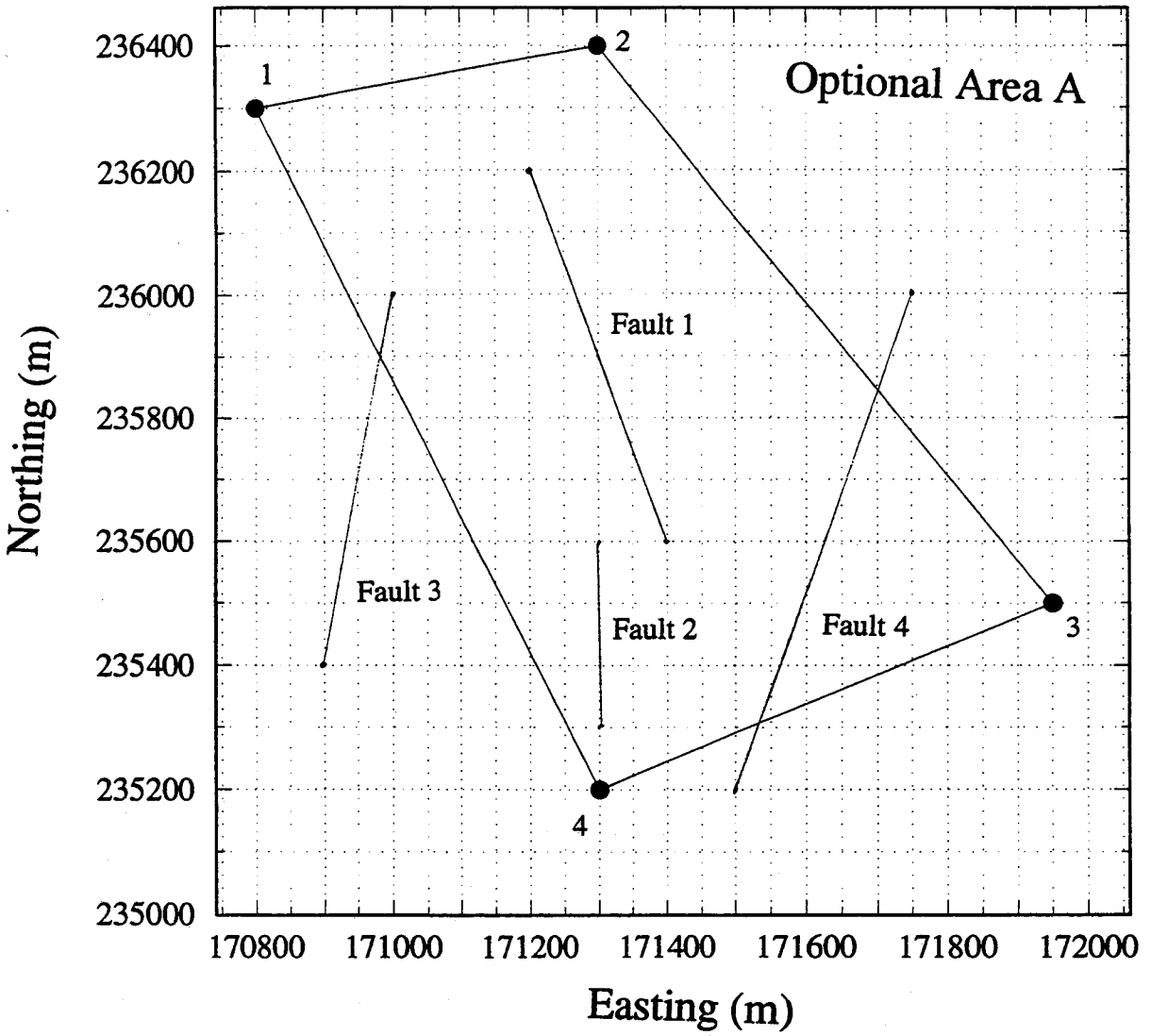

Figure 3-1 Region A with four fault planes used in verification of the code

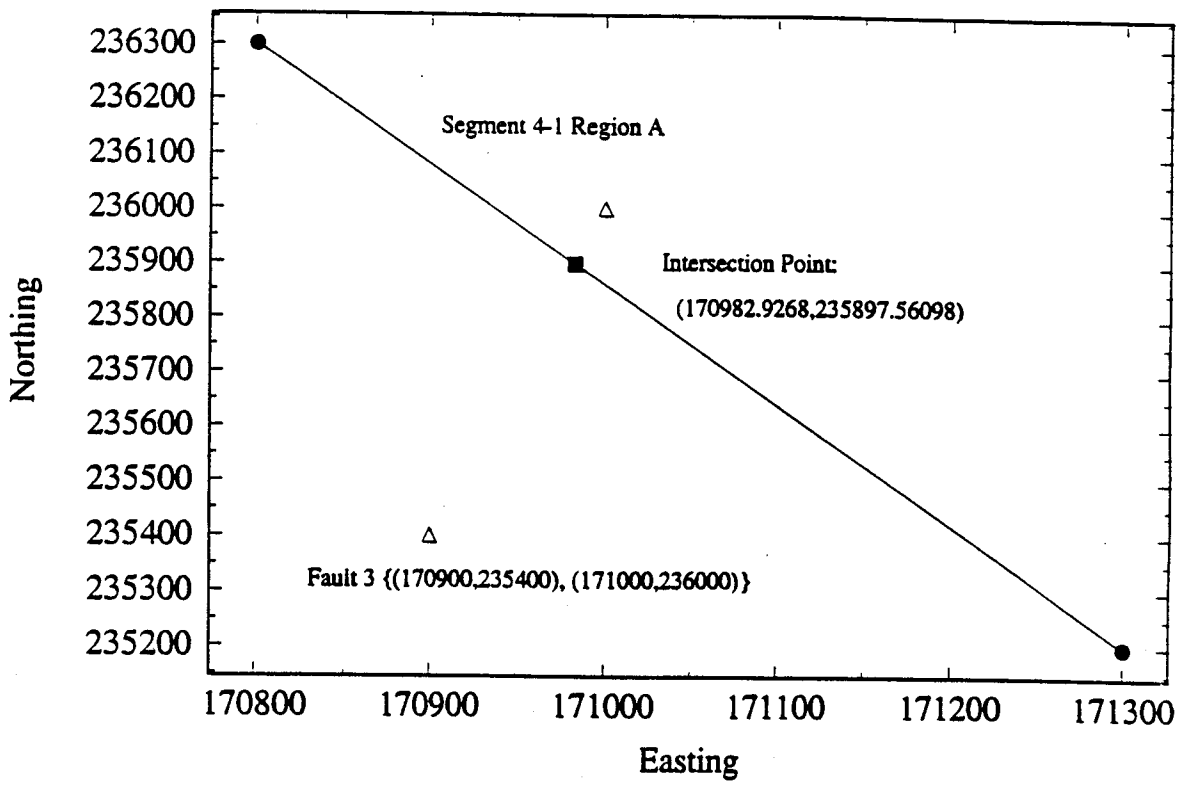

Figure 3-2 Intersection point of Fault 3 and segments of Region A

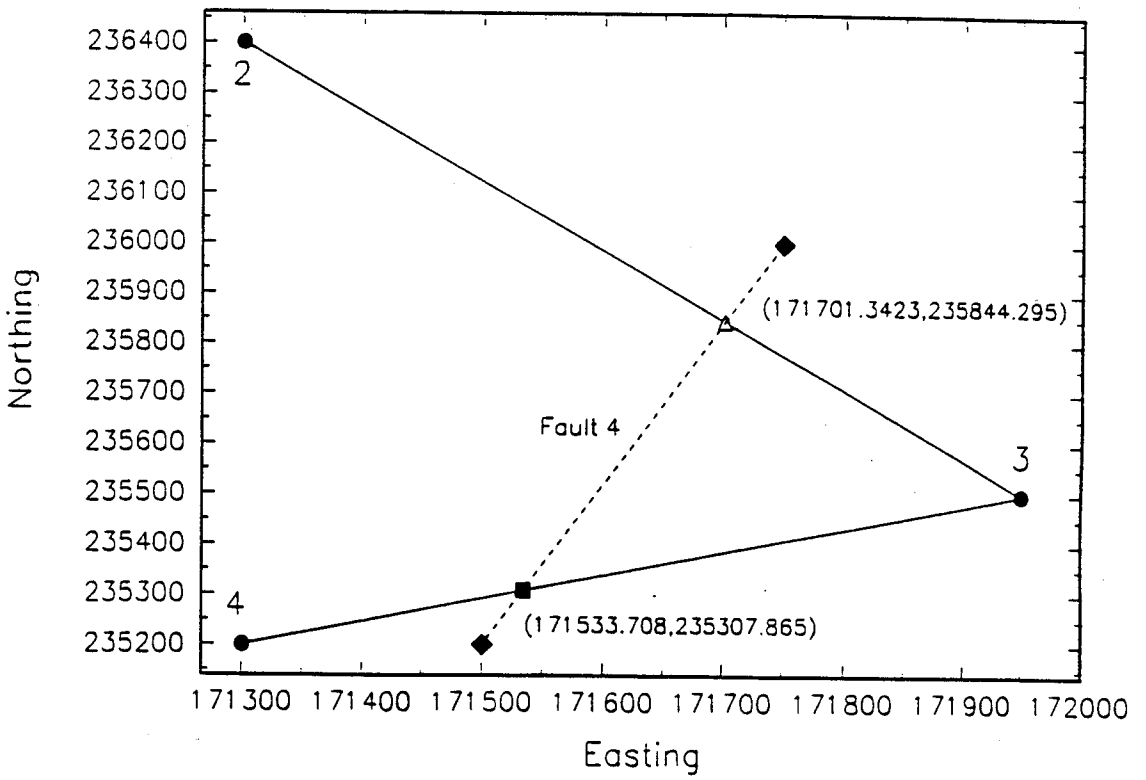

Figure 3-3 Intersection points of Fault 4 and segments of Region A

FAULT 1:

x1 of fault => 171200
y1 of fault => 236200
x2 of fault => 171400
y2 of fault => 235600
Region (PU,PL,A,B,C,D) => A

... Fault Plane ...
End 1: x = 171200.00000000 y = 236200.00000000
End 2: x = 171400.00000000 y = 235600.00000000
Region: A

x(1) = 170800.0 y(1) = 236300.0
x(2) = 171300.0 y(2) = 236400.0
x(3) = 171950.0 y(3) = 235500.0
x(4) = 171300.0 y(4) = 235200.0
x(5) = 170800.0 y(5) = 236300.0

171200.00000000 236200.00000000 falls inside the region
171400.00000000 235600.00000000 falls inside the region

Intersection Points:
Point 1: 171200.00000000 236200.00000000
Point 2: 171400.00000000 235600.00000000
Intersected length = 632.45553203368

Another run => y

FAULT 2:

x1 of fault => 171300
y1 of fault => 235600
x2 of fault => 171300
y2 of fault => 235300
Region (PU,PL,A,B,C,D) => A

... Fault Plane ...
End 1: x = 171300.00000000 y = 235600.00000000
End 2: x = 171300.00000000 y = 235300.00000000
Region: A

x(1) = 170800.0 y(1) = 236300.0
x(2) = 171300.0 y(2) = 236400.0
x(3) = 171950.0 y(3) = 235500.0

x(4) = 171300.0 y(4) = 235200.0
x(5) = 170800.0 y(5) = 236300.0

171300.00000000 235600.00000000 falls inside the region
171300.00000000 235300.00000000 falls inside the region

Intersection Points:
Point 1: 171300.00000000 235600.00000000
Point 2: 171300.00000000 235300.00000000
Intersected length = 300.00000000000

Another run => y

FAULT 3:

x1 of fault => 170900
y1 of fault => 235400
x2 of fault => 171000
y2 of fault => 236000
Region (PU,PL,A,B,C,D) => A

... Fault Plane ...
End 1: x = 170900.00000000 y = 235400.00000000
End 2: x = 171000.00000000 y = 236000.00000000
Region: A

x(1) = 170800.0 y(1) = 236300.0
x(2) = 171300.0 y(2) = 236400.0
x(3) = 171950.0 y(3) = 235500.0
x(4) = 171300.0 y(4) = 235200.0
x(5) = 170800.0 y(5) = 236300.0

170900.00000000 235400.00000000 falls outside the region
171000.00000000 236000.00000000 falls inside the region

In subroutine Intersection
x1 = 170800.00000000 y1 = 236300.00000000
x2 = 171300.00000000 y2 = 236400.00000000
x3 = 170900.00000000 y3 = 235400.00000000
x4 = 171000.00000000 y4 = 236000.00000000
Part 1 = -16078881000000. Part 2 = 16128488000000.
Part 4 = -27817218000000. Part 5 = 27885760000000.
Part 6 = -10000.0000000000 Part 7 = 300000.00000000
xi = 171058.62068966 yi = 236351.72413793

Subroutine Inlength

Data about Intersection:
Segment: 1
x1 = 170800.00000000 y1 = 236300.00000000
x2 = 171300.00000000 y2 = 236400.00000000
Intersection Point:
xi = 171058.62068966 yi = 236351.72413793
A = 356.57573453473 B = 964.85198756455 C = 246.15956272518
D = 263.74238863410 E = 509.90195135928 F = 608.27625302982

In subroutine Intersection
x1 = 171300.00000000 y1 = 236400.00000000
x2 = 171950.00000000 y2 = 235500.00000000
x3 = 170900.00000000 y3 = 235400.00000000
x4 = 171000.00000000 y4 = 236000.00000000
Part 1 = -22099812000000. Part 2 = 22181945000000.
Part 4 = -36235122000000. Part 5 = 36348720000000.
Part 6 = 90000.000000000 Part 7 = 390000.00000000
xi = 171110.41666667 yi = 236662.50000000

Subroutine Inlength
Data about Intersection:
Segment: 2
x1 = 171300.00000000 y1 = 236400.00000000
x2 = 171950.00000000 y2 = 235500.00000000
Intersection Point:
xi = 171110.41666667 yi = 236662.50000000
A = 671.63836272043 B = 1279.9146157502 C = 1433.9827138467
D = 323.80254828797 E = 1110.1801655587 F = 608.27625302982

In subroutine Intersection
x1 = 171950.00000000 y1 = 235500.00000000
x2 = 171300.00000000 y2 = 235200.00000000
x3 = 170900.00000000 y3 = 235400.00000000
x4 = 171000.00000000 y4 = 236000.00000000
Part 1 = 30198825000000. Part 2 = -30260324000000.
Part 4 = 35966766000000. Part 5 = -36051360000000.
Part 6 = 30000.000000000 Part 7 = -390000.00000000
xi = 170830.55555556 yi = 234983.33333333

Subroutine Inlength
Data about Intersection:
Segment: 3
x1 = 171950.00000000 y1 = 235500.00000000
x2 = 171300.00000000 y2 = 235200.00000000
Intersection Point:
xi = 170830.55555556 yi = 234983.33333333

A = 1030.6903176339 B = 422.41406460403 C = 517.03242728497
D = 1232.9234804488 E = 715.89105316382 F = 608.27625302982

In subroutine Intersection
x1 = 171300.00000000 y1 = 235200.00000000
x2 = 170800.00000000 y2 = 236300.00000000
x3 = 170900.00000000 y3 = 235400.00000000
x4 = 171000.00000000 y4 = 236000.00000000
Part 1 = 24143916000000. Part 2 = -24214019000000.
Part 4 = 27760722000000. Part 5 = -27857440000000.
Part 6 = -110000.00000000 Part 7 = -300000.00000000
xi = 170982.92682927 yi = 235897.56097561

Subroutine Inlength
Data about Intersection:
Segment: 4
x1 = 171300.00000000 y1 = 235200.00000000
x2 = 170800.00000000 y2 = 236300.00000000
Intersection Point:
xi = 170982.92682927 yi = 235897.56097561
A = 103.852043200217 B = 504.42420982961 C = 442.06265757053
D = 766.24193978893 E = 1208.3045973595 F = 608.27625302982
Intersection is real

k = 2 xin(k) = 170982.92682927 yin(k) = 235897.56097561

Intersection Points (In subroutine segment):
Point 1: 171000.00000000 236000.00000000
Point 2: 170982.92682927 235897.56097561
Intersection Points:
Point 1: 171000.00000000 236000.00000000
Point 2: 170982.92682927 235897.56097561

Intersected length = 103.852043200217

Another run => y

FAULT 4:

x1 of fault => 171500
y1 of fault => 235200
x2 of fault => 171750
y2 of fault => 236000
Region (PU,PL,A,B,C,D) => A

... Fault Plane ...

End 1: x = 171500.00000000 y = 235200.00000000
End 2: x = 171750.00000000 y = 236000.00000000
Region: A

x(1) = 170800.0 y(1) = 236300.0
x(2) = 171300.0 y(2) = 236400.0
x(3) = 171950.0 y(3) = 235500.0
x(4) = 171300.0 y(4) = 235200.0
x(5) = 170800.0 y(5) = 236300.0

171500.00000000 235200.00000000 falls outside the region
171750.00000000 236000.00000000 falls outside the region

In subroutine Intersection
x1 = 170800.00000000 y1 = 236300.00000000
x2 = 171300.00000000 y2 = 236400.00000000
x3 = 171500.00000000 y3 = 235200.00000000
x4 = 171750.00000000 y4 = 236000.00000000
Part 1 = -10078252500000.0 Part 2 = 10142720000000.0
Part 4 = -27811224000000. Part 5 = 27899920000000.
Part 6 = -25000.000000000 Part 7 = 400000.00000000
xi = 171913.33333333 yi = 236522.66666667

Subroutine Inlength
Data about Intersection:
Segment: 1
x1 = 170800.00000000 y1 = 236300.00000000
x2 = 171300.00000000 y2 = 236400.00000000
Intersection Point:
xi = 171913.33333333 yi = 236522.66666667
A = 547.59311739851 B = 1385.7458481105 C = 625.47972700072
D = 1135.3816783600 E = 509.90195135928 F = 838.15273071201

In subroutine Intersection
x1 = 171300.00000000 y1 = 236400.00000000
x2 = 171950.00000000 y2 = 235500.00000000
x3 = 171500.00000000 y3 = 235200.00000000
x4 = 171750.00000000 y4 = 236000.00000000
Part 1 = -16094895000000. Part 2 = 16222812500000.
Part 4 = -36045576000000. Part 5 = 36221280000000.
Part 6 = 225000.00000000 Part 7 = 520000.00000000
xi = 171701.34228188 yi = 235844.29530201

Subroutine Inlength
Data about Intersection:
Segment: 2

x1 = 171300.00000000 y1 = 236400.00000000
x2 = 171950.00000000 y2 = 235500.00000000
Intersection Point:
xi = 171701.34228188 yi = 235844.29530201
A = 163.13039725267 B = 675.02233345934 C = 424.69979487818
D = 685.48037068055 E = 1110.1801655587 F = 838.15273071201
Intersection is real

k = 1 xin(k) = 171701.34228188 yin(k) = 235844.29530201

In subroutine Intersection
x1 = 171950.00000000 y1 = 235500.00000000
x2 = 171300.00000000 y2 = 235200.00000000
x3 = 171500.00000000 y3 = 235200.00000000
x4 = 171750.00000000 y4 = 236000.00000000
Part 1 = 36342427500000. Part 2 = -36418760000000.
Part 4 = 35989128000000. Part 5 = -36093840000000.
Part 6 = 75000.000000000 Part 7 = -520000.00000000
xi = 171533.70786517 yi = 235307.86516854

Subroutine Inlength
Data about Intersection:
Segment: 3
x1 = 171950.00000000 y1 = 235500.00000000
x2 = 171300.00000000 y2 = 235200.00000000
Intersection Point:
xi = 171533.70786517 yi = 235307.86516854
A = 725.14337376209 B = 113.00935694992 C = 257.39903035103
D = 458.49202281278 E = 715.89105316382 F = 838.15273071201
Intersection is real

k = 2 xin(k) = 171533.70786517 yin(k) = 235307.86516854

In subroutine Intersection
x1 = 171300.00000000 y1 = 235200.00000000
x2 = 170800.00000000 y2 = 236300.00000000
x3 = 171500.00000000 y3 = 235200.00000000
x4 = 171750.00000000 y4 = 236000.00000000
Part 1 = 30240840000000. Part 2 = -30356547500000.
Part 4 = 27543096000000. Part 5 = -27701680000000.
Part 6 = -275000.00000000 Part 7 = -400000.00000000
xi = 171418.51851852 yi = 234939.25925926

Subroutine Inlength
Data about Intersection:
Segment: 4

```
x1 =    171300.00000000 y1 =    235200.00000000
x2 =    170800.00000000 y2 =    236300.00000000
Intersection Point:
xi =    171418.51851852 yi =    234939.25925926
A =     1111.3284355367 B =     273.17570482465 C =     1494.7175389558
D =     286.41294159630 E =     1208.3045973595 F =     838.15273071201
Intersection Points:
Point 1:    171701.34228188    235844.29530201
Point 2:    171533.70786517    235307.86516854

Intersected length =    562.01297650942


                    Another run => n
```

[Amitava Ghosh, June 7, 1996]

3.2. Simulation of Uniformly Distributed Random Numbers Between [0,1]

Uniformly distributed random numbers between 0 and 1 are simulated using the *drand(k)* function of SUNf77 compiler where k>0 starts a new sequence of random numbers and k = 0 gives the next random number in the sequence. *drand(k)* function gives the double precision random numbers.

Using these random numbers, a set of random numbers uniformly distributed between [a,b] can be generated from

$$y = (b - a)\, x + a$$

where,
x = uniform random number between [0,1]
y = uniform random number between [a,b].

A subroutine to generate uniformly distributed random numbers between [0,1], called *random*, is left in the file *fault.f* although it was not used to generate the uniformly distributed random numbers. This subroutine may be used in place of the *drand(k)* function with some modifications of the procedure for calling for the random number in *fault.f* as this subroutine requires the previous random number as seed for generation for next random number.

[Amitava Ghosh, June 27, 1996]

3.3. Simulation of Normally Distributed Random Numbers

A subroutine *gauss* has been developed following the mathematical guideline given in Section 2.1.4 and adopting the routine given in Ghosh and Kulatilake (1987). A set of 500 normally distributed random numbers with a probability 90% falling between [-1, 1] was generated. The statistics of the generated numbers are given below:

	Input Data	**Normal(3.74e-3,0.59)**
Minimum	-1.584767	
Maximum	1.966892	
Mode	-0.128587	3.743165e-3
Mean	3.743165e-3	3.743165e-3
Std Deviation	0.586337	0.586337
Variance	0.343791	0.343791
Skewness	0.119546	0.0
Kurtosis	3.05641	3.0

Best Fit Results	
C-S Test	57.136959
K-S Test	0.023695
A-D Test	0.231722

Figure 3-4 shows the histogram of random numbers with a fitted normal distribution with mean and standard deviation equal to 0.0037 and 0.5863 respectively. They compare very well with the population mean and standard deviation equal to 0.0 and 0.6079 respectively. The skewness and kurtosis of the data set indicate normality. Figure 3-5 shows the cumulative distribution of these numbers. The numbers were tested for normality. The data set passes Kolmogorov-Smirnov (K-S) test for goodness-of-fit with $\alpha = 0.05$. As expected, with a larger set of random numbers, the sample mean and standard deviation become closer to the population mean and standard deviation. This has been tested with different data sets. For example, when the number of generated random numbers is 1000, the sample mean and standard deviation are 0.0012 and 0.5987 respectively, as shown below. The skewness and kurtosis of the data set have improved quite a bit.

	Input Data	**Normal(1.25e-3,0.60)**
Minimum	-2.051897	
Maximum	1.859709	
Mode	-0.056978	1.249021e-3
Mean	1.249021e-3	1.249021e-3
Std Deviation	0.598718	0.598718
Variance	0.358463	0.358463

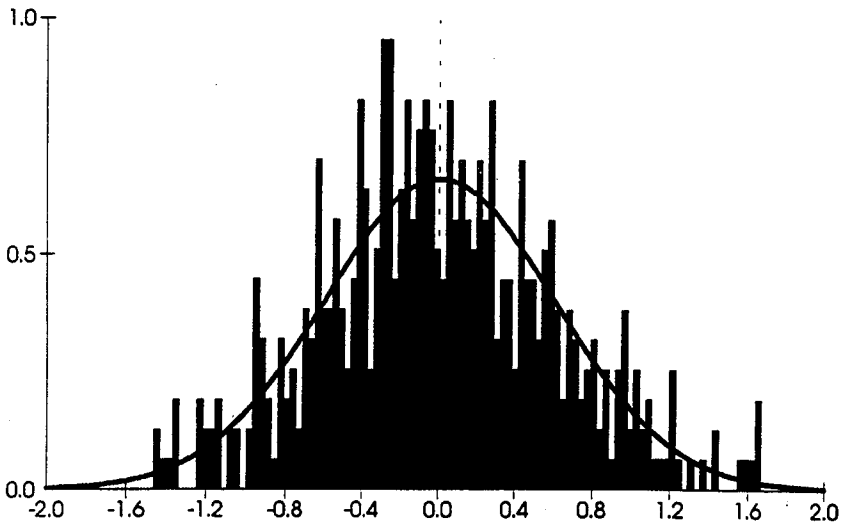

Figure 3-4 Histogram of random numbers, generated by *gauss*, having normal distribution

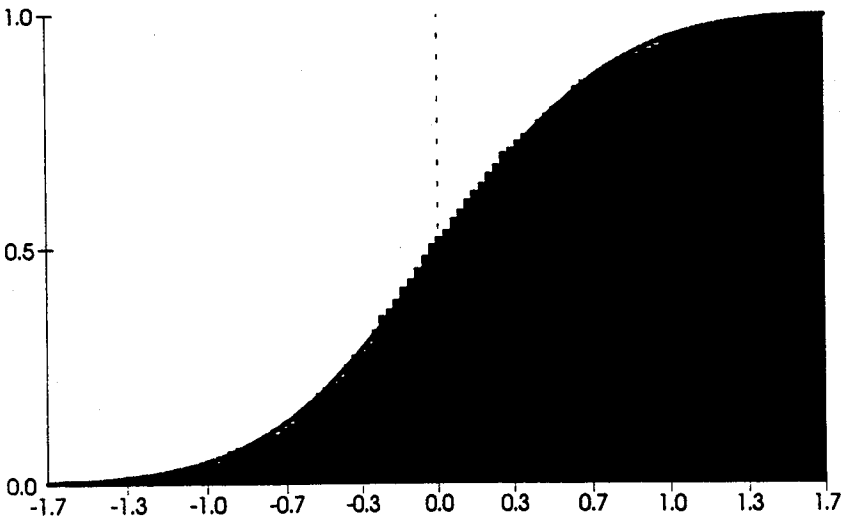

Figure 3-5 Cumulative distribution of random numbers generated by *gauss* having normal distribution

Skewness	-0.012203	0.0
Kurtosis	2.969442	3.0

Best Fit Results

C-S Test	37.568098
K-S Test	8.731377e-3
A-D Test	0.077632

[Amitava Ghosh, June 28, 1996]

3.4. Simulation of Beta Distributed Random Numbers

A subroutine *betad* has been developed following the mathematical guideline given in Section 2.1.5 with any acceptable values of α and β. In the file *fault.inc*, the values of α and β are fixed as 1.5 and 3.0, as given in Stirewalt et al. (1995). A set of 1000 random numbers between [0, 1] was generated. Sample statistics show that sample α and β are 1.50 and 3.11 respectively. Sample mean and variance are 0.3279 and 0.0390 respectively which compare very well with population mean of 0.3333 and population variance of 0.0404. Figure 3-6 shows the histogram of random numbers with beat distribution fitted over it.

	Input Data	**Beta(1.50,3.11) + 2.92e-3**
Minimum	2.91705e-3	
Maximum	0.92994	
Mode	0.206862	0.191073
Mean	0.327924	0.325007
Std Deviation	0.197694	0.197694
Variance	0.039083	0.039083
Skewness	0.485402	0.535402
Kurtosis	2.421904	3.38095

Best Fit Results

C-S Test	13.767742
K-S Test	0.013351
A-D Test	0.258163

[Amitava Ghosh, June 28, 1996]

3.5. Verification of Subroutine *exponential*

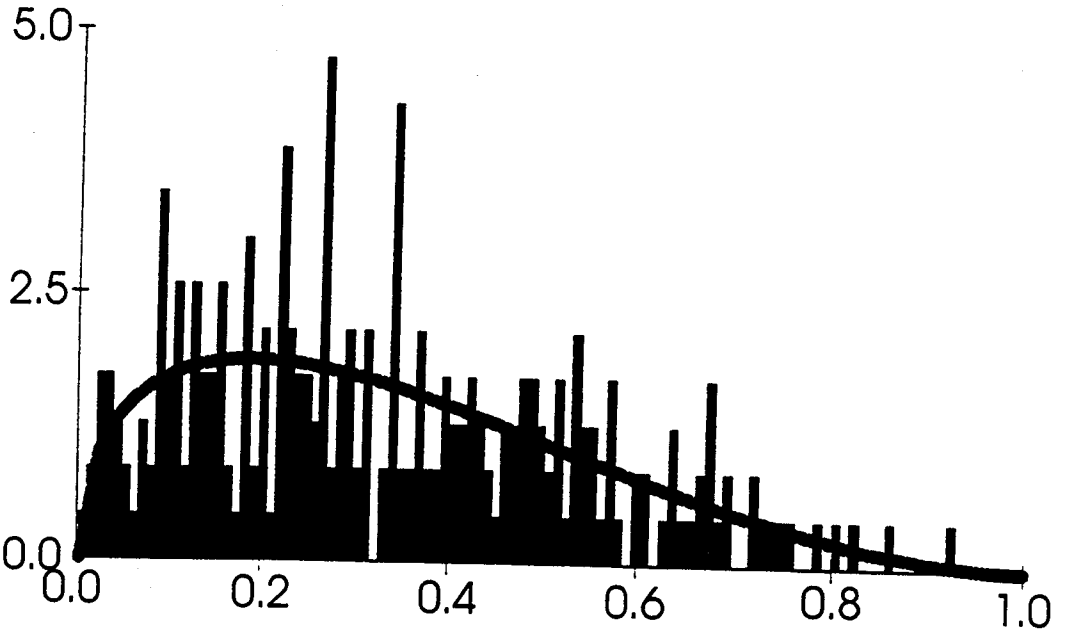

Figure 3-6 Histogram of random numbers generated by *betad* having beta distribution

Random numbers following the exponential distribution with the parameter λ are simulated using the subroutine *exponential*. The equation used in the subroutine *exponential* is given in Section A.10. A set of 1000 random numbers with λ equal to 10 (mean and standard deviation equal to 0.1) were generated. The statistics of the generated numbers are given below:

	Input Data	**Exponential Distribution**
Minimum	1.85602e-4	
Maximum	0.62722	
Mode	9.59108e-3	
Mean	0.09888	0.09888
Standard Deviation	0.095711	0.09888
Variance	9.16051e-3	9.77780e-3
Skewness	1.75468	2.0
Kurtosis	6.97331	9.0

Best Fit Results

Chi-Square Test	113.74484
Kolmogorov-Smirnov Test	0.02051
Anderson-Darling Test	0.31278

Figure 3-7 shows the histogram of generated random numbers with a fitted exponential distribution. The mean and standard deviation compare very well with the given λ. Goodness-of-fit analysis with Chi-Square, Kolmogorov-Smirnov, and Anderson-Darling tests show that the data set is exponential with α equal to 0.05.

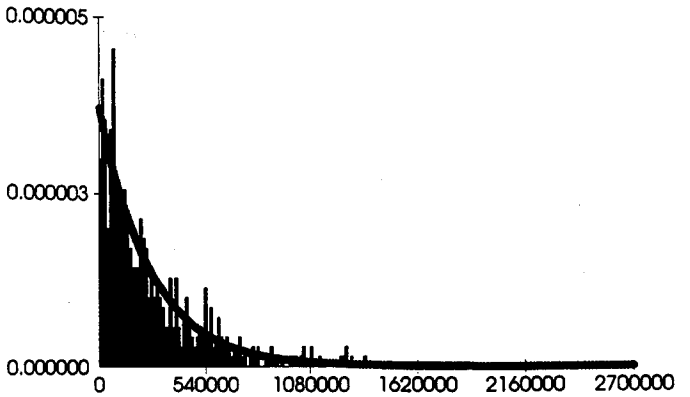

Figure 3-7. Histogram of random numbers generated by exponential distribution

[Amitava Ghosh, December 15, 1996]

3.6. Verification of Subroutine *check_disrupt*

Subroutine *check_disrupt* has been verified by developing a small test program which basically supplies the values of all input variables of the subroutine and prints the output on the screen. These results were checked using hand-calculation.

A typical output for verification run of the subroutine *check_disrupt* is given below. For this particular run, a fault having length of 1000 m within the given repository was assumed. The fault had a width of 10 m. Each waste package contained 10 MTU of waste. Waste packages were emplaced at an AML of 100 MTU/acre. There is no standoff distance. The area affected should be equal to 10000 m^2 or 2.47097 acre. Number of waste packages disrupted should be equal to 25 or 0.36 percent of all waste packages.

```
                    length => 1000

                     width => 10

                  standoff => 0

                       AML => 100

                    MTU_wp => 10
 Number of waste packages disrupted = 25
 Percent of waste packages disrupted = 0.35709184408188 percent
 Area disrupted =      2.4709700000000 acre
```

[Amitava Ghosh, December 15, 1996]

3.7. Verification of Subroutine *sort*

Subroutine *sort* of Press et al. (1986) has been verified using a small test program which takes the values of all elements in an array and calls the subroutine *sort* to rearrange them in an ascending order. It then prints the rearranged values on the screen. A typical example of the verification run is given below.

```
                    number of data => 20
 Data   1 => 1
 Data   2 => 4
```

```
Data  3 => 5
Data  4 => 6
Data  5 => 7
Data  6 => 8
Data  7 => 2
Data  8 => 3
Data  9 => 20
Data 10 => 19
Data 11 => 18
Data 12 => 10
Data 13 => 11
Data 14 => 12
Data 15 => 17
Data 16 => 16
Data 17 => 13
Data 18 => 15
Data 19 => 14
Data 20 => 0
  0.
    1.0000000000000
    2.0000000000000
    3.0000000000000
    4.0000000000000
    5.0000000000000
    6.0000000000000
    7.0000000000000
    8.0000000000000
   10.0000000000000
    11.000000000000
    12.000000000000
    13.000000000000
    14.000000000000
    15.000000000000
    16.000000000000
    17.000000000000
    18.000000000000
    19.000000000000
    20.000000000000
```

[Amitava Ghosh, December 15, 1996]

3.8. Verification of Function *drand_a()*

Function drand_a() was verified using a small test program which gives a seed to drand_a() and generated a specified number of uniformly distributed sample by calling the function drand_a(). A typical example of the verification run is given below. A total of 5000 random samples were generated. Only first 50 are show below for clarity. The histogram of all 5000 samples are shown in Figure 3-8.

0.31846297128054
0.40715831211170
0.10975166135922
0.59617246435777
0.87060846102918
0.31640451742169
0.81072430629783
0.84341594755809
0.29183060875713
0.79704138114911
0.87449297303077
0.60339772822494
0.30561827649624
0.52637307230680
0.75222626037534
0.66675812828669
0.20386211443872
0.31055737161569
0.53774474493123
0.87592805916254
0.72289034478501
0.61802480165755
0.14284145838713
0.73639111255128
0.52542864928275
0.87930849514869
0.53787796410633
0.11494273511457
0.84254907064259
0.72223028993338
0.52448291029990
0.98427341039492
0.68320850733817
0.68538283262652
0.22926795400179
0.30650290814531
0.39437719825393
0.29757105386703
0.27670234314944
0.53628131259991
0.28002086667345
0.31070618066504

3.8778437319574D-02
0.74919603008274
0.73767760057825
0.14743291872900
0.90506507824411
0.42877004874347
0.33820923154159
0.28255451949432

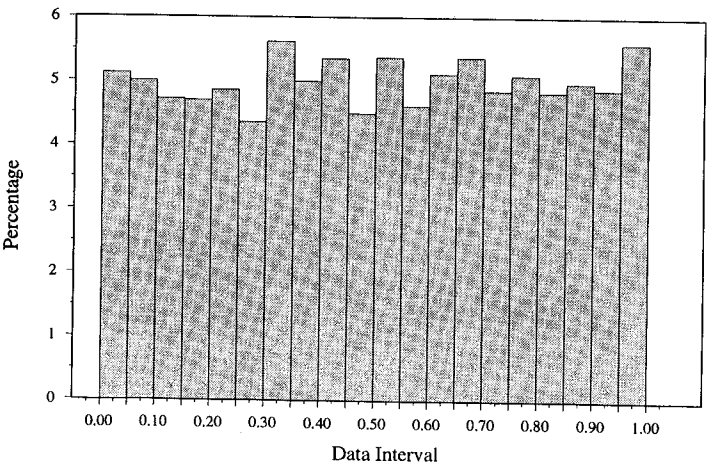

Figure 3.8. Histogram of 5000 random number generated using drand_a function

4. OTHER FEATURES

4.1. Date and Time Stamp

This code will write the date and time of running on the output file. It uses the *fdate()* function from the SUNf77 library.

[Amitava Ghosh, June 27, 1996]

4.2. File for Plotting the Faults and the Repository Region

At present, CNWRA does not have any software which can plot the faults and the repository while the module is running. Only available software is a freeware called PLOTMTV which does a decent

header information for formatting and manipulating the visual look of the plot. The FAULTING module automatically writes the necessary information to the plotting files for processing by PLOTMTV. In most cases, the plot file will run without any modification on PLOTMTV and produce a decent plot. User may want to change the plot file for enhancement of the plot. PLOTMTV can produce a postscript output for plotting on postscript printer. Present setup in the FAULTING module only produces black and white output. With trivial modification and proper setting of PLOTMTV program, a color output can be generated.

[Amitava Ghosh, June 27, 1996]

4.3. Development of Check for Emplacement Area Requirement

At the beginning of the simulation, the code checks whether the emplacement area available in Primary Upper region is sufficient to dispose 70,000 MTU of waste at the Areal Mass Loading (AML) (MTU/acre) specified before. If the available area is not sufficient, next emplacement region check is primary Lower. If the area is still not sufficient, the Optional Area A, Optional Area B, Option Area C, and Optional Area D will be checked in this sequence. The program keeps track of all the emplacement regions necessary to run a specific case. The program checks all the necessary emplacement regions and sums the length of the fault in each region to calculate the length of a fault within the repository.

[Amitava Ghosh, December 20, 1996]

4.4. Development of User's Manual

A user's manual for the FAULTING module has been prepared. It is named "FAULTIMG Version 1.0 – A Code for Simulation of Direct Fault Disruption Technical Description and User's Guide" (CNWRA 97-002), authored by A. Ghosh, R.D. Manteufel, and G. Stirewalt. The report documents the technical details, mathematical theories, details of compilation of the code, and required input and output of the code. Results of verification of the subroutines used in the code are also given.

[Amitava Ghosh, January 30, 1997]

4.5. Quality Assurance Status

The FAULTING module is not currently under TOP-018 but will be placed under control when Total-system Performance Assessment version 3 (TPA 3) code is placed under TOP-018.

[Amitava Ghosh, February 12, 1996]

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[Amitava Ghosh, June 28, 1996]

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[Amitava Ghosh, December 20, 1996]

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[Amitava Ghosh, January 31, 1997]

I have reviewed this section the notebook and find it to comply with QAP-003. There is sufficient detail so that another qualified individual could repeat the work described. RG Baca 2/14/97

CENTER FOR NUCLEAR WASTE REGULATORY ANALYSES

QA RECORDS PROCESSING WORKSHEET

Record Title:	Scientific Notebook #167 printed April 30, 1997 for Development of the FAULTING Module	
Record Date:	04/97	
Author:	Ghosh, A.	**Subject Code:** 308
Project Number:	20-5708-762	**Retain Until:** Permanent

Record Package Contents	Number of Pages
Scientific Notebook #167	i-iii
	1-53
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CNWRA Form QAP 16

Re: Second Call for Electronic Scientific Notebooks - July 1

To: BMABRITO (BMABRITO) at cnwra-os2
From: Amitava Ghosh
Subject: Re: Second Call for Electronic Scientific Notebooks - July 1
07-22-97 03:39 PM

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At the present time, printed copies of electronic scientific notebooks have been
received from A. Armstrong, B. Hill, R. Chen, and S. Hsiung from the July 1, 1997 "quarterly call."

The following scientific notebooks have not yet been received:
095E
163E
115E
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205E
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Some of these may be in the "printing phase" which can take up to three weeks depending on the Printing Shop backlog. However, if you "own" one of these electronic scientific notebooks and you are not printing it yet, please call me.
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Bruce Mabrito x 5149

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Bruce,

I have not written anything to **the Scientific Notebook No. 167E** for the period ending in June 30, 1997.

Thanks,

Amit Ghosh
x3314

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Scientific Notebook #167
printed April 30, 1997 for
Development of the FAULTING

SCIENTIFIC NOTEBOOK
Development of the FAULTING Module

by

Amitava Ghosh

Southwest Research Institute
Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas

April 30, 1997

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1. INITIAL ENTRIES

Scientific NoteBook: # 167

Issued to: Amitava Ghosh

Issue Date: February 28, 1996

Printing Period: February 1 through April 30, 1997

Project Title: Development of the FAULTING Module of Phase 3 IPA

Project Staff: Amitava Ghosh

By agreement with the CNWRA QA this NoteBook is to be printed at approximate quarterly intervals. This computerized Scientific NoteBook is intended to address the criteria of CNWRA QAP-001.

[Amitava Ghosh, April 29, 1997]

1.1. Objectives

The objective of this activity is to develop the FORTRAN coding of the faulting consequence (FAULTING) module for the Phase 3 of the Nuclear Regulatory Commission (NRC) Iterative Performance Assessment (IPA) activity. The basic approach to the FAULTING module has been described in Stirewalt et al. (1995). Taking into account the published data for faults at Yucca Mountain area, this module provides a framework for determining if the primary fault displacement (that is, displacement along the main fault trace rather than along associated secondary fractures) in the repository block could induce waste package disruption, the timing of that disruption, and the number of waste packages disrupted.
[Amitava Ghosh, February 28, 1996]

1.2. Technical Approaches

The codes for the FAULTING module will be written in Fortran 77. Fault displacement is generated in the FAULTING module along an assumed, unknown, and randomly located fault zone inside the simulation area. These unknown fault zones include those not distinguished or adequately characterized, as well as new faults which may develop during the 10,000 year regulatory time frame of interest. Strike direction is determined as either northeast or northwest observed in the field at and near Yucca Mountain. Whether the fault intersects the potential repository depends on location and orientation of the fault in the simulation area and total fault trace length. Whether waste packages are disrupted is dependent upon amount of displacement exceeding a threshold value which is governed by repository and waste package

design and waste package emplacement geometry. If the threshold displacement is exceeded by either largest credible displacement in a single event or by smaller cumulative displacements with time through multiple events, then number and locations of waste packages intersected and disrupted can be calculated based on length of intersection of the fault zone with the repository, repository design, and waste package emplacement geometry. Location, trace orientation, geometry, activity, number and time and amount of largest credible displacement faulting events, and amount and time of cumulative displacements are chosen randomly from range of published data represented as probability distribution functions (PDFs). It is assumed that the unknown fault zones can possess attributes similar to those of the Ghost Dance and Sundance faults. The fault zone is assigned a randomly selected width, and displacement in the zone is considered along both single and multiple slip surfaces. It is assumed that the variation in dip of the fault has little influence on number of waste packages disrupted, considering horizontal emplacement. If waste package disruption occurs as a result of either a largest credible displacement event or cumulative displacement, the timing of that disruption is relayed to the SOurce TErm Code (SOTEC) for calculation of radionuclide release.

The random numbers following a particular PDF will be generated primarily using the program LHS94 (version 1.1) (Iman and Shortencarier, 1984) which uses the Latin Hypercube method. However, using the LHS94 program is a two step process. All the random numbers needed to run the FAULTING modules should be known beforehand and need to generated in advance of running the module. The final version of the FAULTING module will have an user interface to do this. Additionally, each subroutine of the FAULTING module may use own random number generation routines during development. Currently, the LHS94 code is not under the code configuration management of CNWRA.

[Amitava Ghosh, February 28, 1996]

The code in the present form has own subroutines to generate necessary random numbers from a given distribution. Therefore, at this point, there is no need to generate the random numbers using the LHS routines before the run and use them while running this module. At present, this is quite a cumbersome process as we have to estimate beforehand how many random numbers from each specific distribution is needed. It may also be extremely difficult to guess beforehand as the number of random numbers needed for any simulation drastically goes down if the generated fault does not intersect the given repository region.

[Amitava Ghosh, June 27, 1996]

It was also decided to carry out the complete calculation in double precision. The reason is as follows. In the calculation done by this module, we are dealing with very large numbers (coordinates of the faults) and very small numbers (slipping rate on a fault surface). In both cases, it becomes necessary to keep enough precision in the calculations (at least more than 6 significant digits) so that rounding off error does not mislead the calculation sequence.

[Amitava Ghosh, June 27, 1996]

1.3. Computers, Computer Codes, and Data Files

Table 1-1. Computer, operating system, and compiler to be used in developing FAULTING module

Machine Name	Machine Type	Operating System	Compiler	Location
snowwhite	SUN SPARCstation 20	SUNOS 4.1	f77 (SUN)	Building 189

[Amitava Ghosh, February 28, 1996]

1.4. Mathematical Theory

Not Applicable

[Amitava Ghosh, February 28, 1996]

Two modifications of the algorithm given in Stirewalt et al. (1995) were carried out in this period:

1. Flow chart for calculation of largest credible displacement along single and multiple slip surfaces given in Stirewalt et al. (1995) has been modified to (i) reduce unnecessary calculations, and (ii) carry out the sequence of calculations in a more logical way.

Previously, after randomly generating the largest credible displacement, this amount of displacement was partitioned among 2 to 4 randomly generated slip surfaces of the same fault plane. Thereafter, the slip along each of the multiple surfaces was compared against the threshold value. If failure occurs on any of the multiple slip surfaces of the fault plane, the check for slippage on the fault plane itself. This procedure has been modified to allow the flow of calculation in a more logical way and to eliminate unnecessary calculations.

In the present procedure, once the largest credible displacement is randomly generated for a given fault plane, the displacement is compared with the threshold displacement TD for waste packages, based on a uniform pdf varying between 0.1 and 0.5 m. If only failure is indicated, the total displacement on this fault plane is partitioned among 2 to 4 slip surfaces generated randomly. Displacement on each of these slip surfaces is compared with the threshold displacement TD.

New flow chart is given in Figure 1-1. The code necessary to determine the number of waste packages being disrupted due to the faulting event is under development.

[Amitava Ghosh, August 18, 1996]

2. Previously, comparison of displacement along any of the slip surfaces was carried out against LDmax, which was set to 0.045 m. This is not correct as the correct comparison should be against the threshold displacement for waste package rupture, TD. The code has been modified to reflect this.

[Amitava Ghosh, August 18, 1996]

Algorithm to calculate fault displacement along multiple surfaces has been changed again after consultation with Drs. John Stamatokos and D. Ferrill. In the present algorithm, calculation for single and multiple surfaces are carried out independent of each other. Number of slip surfaces is simulated at the time of generating the fault geometrical parameters.

[Amitava Ghosh, November 15, 1996]

Previously, the threshold displacement for waste package disruption was a random variable varying uniformly between 0.1 m and 0.5 m. After discussion with Dr. B. Sagar, this has been changed to a user-specified variable. At the beginning of the simulation, user is asked interactively to input a specific value for this variable.

[Amitava Ghosh, November 20, 1996]

The new flow chart is given in Figure 1-2.

[Amitava Ghosh, January 28, 1997]

1.5. Assumptions

The assumptions for each of the parameters and the complete module are given in Stirewalt et al. (1995). [Amitava Ghosh, February 28, 1996]

1.6. Initial/Boundary Conditions

Not Applicable [Amitava Ghosh, February 28, 1996]

2. OTHER FEATURES

2.1. Quality Assurance Status

The FAULTING module is not currently under TOP-018 but will be placed under control when Total-system Performance Assessment version 3 (TPA 3) code is placed under TOP-018.

[Amitava Ghosh, February 12, 1996]

2.2. Change in Tolerance Value of *tol* in Subroutine *inlength*

The tolerance value *tol* in the subroutine *inlength* was set at 1.0 m (assuming all length dimensions are given in meter). The tolerance value is used to determine intersection between two lines. It was considered low enough during development of the code as many length parameters have values in terms of kilometeres. After running millions of simulations with the FAULTING code, it was discovered that in isolated cases (of the order of 1 in 1 million simulations or less), a randomly generated fault may have end points which may be within a distance of less than 1 m from any of the corners of the proposed repository. Consequently, this tolerance value was generating a false intersection between the fault and boundaries of the proposed repository. The tolerance value has been decreased to 1 mm (1.0d-03) which has solved the problem. Several million realizations carried out after the modification did not have this spurious intersection problem.

[Amitava Ghosh, April 29, 1997]

3. DEVELOPMENT OF FAULTO MODULE FOR TPA 3.0 FROM THE STANDALONE VERSION FAULTING 1.0

The FAULTING code (Version 1.0) is a standalone code suited for sensitivity analyses of different input parameters on the final results. A version of the FAULTING code has been developed which becomes a module of the TPA code (Version 3.0). This module is called FAULTO and essentially has features similar to the FAULTING code with a few exceptions.

3.1. Differences Between FAULTO and FAULTING

The differences are generally minor and necessary so that FAULTO can become a module of the TPA 3.0. The differences are noted below:

(1) Simulation of time of occurrence of a faulting event has been changed. In FAULTING, the recurrence time of a faulting event is uniformly distributed between 60,000 and 275,000 years. These numbers are for Ghost Dance fault and are assumed for all simulated faults. The time of occurrence of the faulting event has an exponential distribution with the mean equal to the reciprocal of the randomly selected recurrence interval from a uniform distribution between 60,000 and 275,000 years. The TPA code cannot simulate this process due to the deficiency of the LHS program (Iman and Shortcarier, 1984) . All the random numbers necessary for a particular run have to be sampled beforehand.

Consequently, the TPA and LHS codes are incapable of sampling from the exponential distribution using the samples from the uniform distribution during runtime.

In the FAULTO module, this problem was addressed by assuming that the recurrence interval is constant and equal to 60,000 years. This will be a conservative assumption. Before the TPA code is run, all necessary values of the time of occurrence are sampled from an exponential distribution with mean equal to 1/60,000 year.

(2) There is no provision for plotting in the FAULTO module.

(3) The outputs from the FAULTO module are the time of occurrence and the percentage of repository area disrupted. Knowing the areal mass density (MTU/acre) of waste package emplacement, percentage of waste packages disrupted due to the faulting event can be calculated. Currently, there is no provision for extracting other results from the FAULTO module such as the fault location, geometry, largest credible displacement etc., although only minor modifications of the code will be necessary to incorporate this feature, if necessary.

(4) The FAULTO module does not simulate multiple slip surfaces of a single fault. All fault displacement is assumed to occur along the fault plane. In the FAULTING code, partitioning of the fault slip (both largest credible event and cumulative fault displacement) among multiple slip surfaces is somewhat arbitrary. The partitioning was based on the equivalent area of influence assigned to each slip surface. Better theoretical/conceptual justification is necessary. It was decided not to incorporate this feature in the FAULTO module right now.

(5) The FAULTO module checks whether a fault falls within the given repository boundaries using its own routines developed from the routines available in the FAULTING code.

(6) The FAULTING code checks for the sufficiency of the emplacement area for 70,000 MTU of waste. It checks first the Primary Upper area. If the available area is insufficient to emplace all waste packages at the specified areal mass loading, the FAULTING code checks for other emplacement areas in the following sequence — Primary Lower area, Optional Area A, Optional Area B, Optional Area C, and Optional Area D until the cumulative emplacement area is sufficient for 70,000 MTU of waste. Similar checking is carried out by the Executive module of the TPA code.

(7) At present, the FAULTO module does not have a provision to include a standoff zone in calculating the area of the repository likely to be affected due to slip on a given fault although the modification necessary will be trivial.

The FAULTO module for the TPA 3.0 code was developed by R. Manteufel from the FAULTING code.

3.2. Testing of the FAULTO Module

The FAULTO module has been tested by writing a driver program called *testfaulto.f* (driver code was written by R. Manteufel). It uses the *tpa.inc* file and generates the percentage of area disrupted in 1,000,000 realizations. Both FAULTO and FAULTING codes were run for several cases with four different threshold displacement levels — 0.1 m, 0.2 m, 0.3 m, and 0.4 m. For each case, at least two different random number seeds were used. As the FAULTO code used 60,000 years as the recurrence interval, the FAULTING code was forced to use the same recurrence interval instead of sampling from the uniform distribution. It should be mentioned here that as FAULTING and FAULTO codes use different random number generators, the random numbers used in the simulations will never be exactly the same but the results should be statistically the same. Results from both codes are summarized below. Sample plots are also attached. Testing of the FAULTO code was done by A. Ghosh.

3.3. Summary of Results Using Standalone FAULTING code

Case 1: Threshold Displacement = 0.1 m
Seed = 1
Number of Realization = 1,000,000

Statistics	Area Disrupted (%)	Time (yr)
Minimum	0.00	16.4
Maximum	28.50	9998.90
Mean	3.94	4940.30
Median	2.36	5103.40
Standard Deviation	4.61	2925.86
Number of Observations	896	896

Annual Probability = 8.96×10^{-8}

Case 2: Threshold Displacement = 0.1 m
Seed = 2
Number of Realization = 1,000,000

Statistics	Area Disrupted (%)	Time (yr)
Minimum	0.00	3.00
Maximum	28.89	9998.40
Mean	3.95	4727.05
Median	2.34	4599.90
Standard Deviation	4.59	2881.27
Number of Observations	896	896

Annual Probability = 8.96×10^{-8}

Case 3: Threshold Displacement = 0.1 m
Seed = 3
Number of Realization = 1,000,000

Statistics	Area Disrupted (%)	Time (yr)
Minimum	0.00	0.60
Maximum	29.74	9996.90
Mean	4.17	4939.74
Median	2.48	4761.00
Standard Deviation	4.77	2877.80
Number of Observations	901	901

Annual Probability = 9.01×10^{-8}

Case 4: Threshold Displacement = 0.1 m
Seed = 4
Number of Realization = 1,000,000

Statistics	Area Disrupted (%)	Time (yr)
Minimum	0.00	12.50
Maximum	27.09	9999.00
Mean	4.11	4791.70
Median	2.49	4681.35
Standard Deviation	4.69	2943.89
Number of Observations	882	882

Annual Probability = 8.82×10^{-8}

Case 5: Threshold Displacement = 0.1 m
Seed = 5
Number of Realization = 1,000,000

Statistics	Area Disrupted (%)	Time (yr)
Minimum	0.00	2.80
Maximum	27.87	9997.20
Mean	4.12	4747.77
Median	2.49	4689.95
Standard Deviation	4.69	2966.20
Number of Observations	884	884

Annual Probability = 8.84×10^{-8}

Case 6: Threshold Displacement = 0.2 m
Seed = 1
Number of Realization = 1,000,000

Statistics	Area Disrupted (%)	Time (yr)
Minimum	0.00	16.40
Maximum	28.50	9998.90
Mean	4.38	4918.44
Median	2.53	4866.20
Standard Deviation	5.01	2924.65
Number of Observations	549	549

Annual Probability = 5.49×10^{-8}

Case 7: Threshold Displacement = 0.2 m
Seed = 2
Number of Realization = 1,000,000

Statistics	Area Disrupted (%)	Time (yr)
Minimum	0.00	7.90
Maximum	28.89	9996.40
Mean	4.30	4805.68
Median	2.67	4681.95
Standard Deviation	4.78	2872.75
Number of Observations	572	572

Annual Probability = 5.72×10^{-8}

Case 8: Threshold Displacement = 0.2 m
Seed = 4
Number of Realization = 1,000,000

Statistics	Area Disrupted (%)	Time (yr)
Minimum	0.00	16.20
Maximum	27.09	9999.00
Mean	4.49	4827.67
Median	2.73	4753.00
Standard Deviation	4.90	2975.74
Number of Observations	571	551

Annual Probability = 5.51×10^{-8}

Case 9: Threshold Displacement = 0.2 m
Seed = 5
Number of Realization = 1,000,000

Statistics	Area Disrupted (%)	Time (yr)
Minimum	0.01	37.40
Maximum	26.19	9997.20
Mean	4.49	4835.07
Median	2.70	4779.90
Standard Deviation	4.92	2995.48
Number of Observations	516	516

Annual Probability = 5.16×10^{-8}

Case 10: Threshold Displacement = 0.3 m
Seed = 1
Number of Realization = 1,000,000

Statistics	Area Disrupted (%)	Time (yr)
Minimum	0.00	31.60
Maximum	28.50	9998.90
Mean	4.64	4917.67
Median	2.93	4768.00
Standard Deviation	5.01	2917.75
Number of Observations	283	283

Annual Probability = 2.83×10^{-8}

Case 11: Threshold Displacement = 0.3 m
Seed = 2
Number of Realization = 1,000,000

Statistics	Area Disrupted (%)	Time (yr)
Minimum	0.00	7.90
Maximum	28.89	9987.70
Mean	4.65	5051.01
Median	3.14	5051.40
Standard Deviation	4.95	2880.86
Number of Observations	293	293

Annual Probability = 2.93×10^{-8}

Case 12: Threshold Displacement = 0.3 m
Seed = 3
Number of Realization = 1,000,000

Statistics	Area Disrupted (%)	Time (yr)
Minimum	0.02	0.60
Maximum	27.20	9996.90
Mean	4.66	4999.03
Median	3.01	4925.60
Standard Deviation	4.88	2882.46
Number of Observations	293	293

Annual Probability = 2.93×10^{-8}

Case 13: Threshold Displacement = 0.3 m
Seed = 4
Number of Realization = 1,000,000

Statistics	Area Disrupted (%)	Time (yr)
Minimum	0.00	16.20
Maximum	27.09	9999.00
Mean	5.04	4965.04
Median	3.04	5065.45
Standard Deviation	5.45	2955.90
Number of Observations	280	280

Annual Probability = 2.80×10^{-8}

Case 14: Threshold Displacement = 0.3 m
Seed = 5
Number of Realization = 1,000,000

Statistics	Area Disrupted (%)	Time (yr)
Minimum	0.01	37.40
Maximum	26.19	9997.20
Mean	4.91	4929.41
Median	2.92	5049.30
Standard Deviation	5.25	2929.90
Number of Observations	258	258

Annual Probability = 2.58×10^{-8}

Case 15: Threshold Displacement = 0.4 m
Seed = 1
Number of Realization = 1,000,000

Statistics	Area Disrupted (%)	Time (yr)
Minimum	0.00	40.90
Maximum	24.07	9773.00
Mean	4.82	4814.70
Median	3.22	4621.35
Standard Deviation	5.35	2882.88
Number of Observations	96	96

Annual Probability = 9.60×10^{-9}

Case 16: Threshold Displacement = 0.4 m
Seed = 2
Number of Realization = 1,000,000

Statistics	Area Disrupted (%)	Time (yr)
Minimum	0.03	95.10
Maximum	28.89	9952.30
Mean	4.77	5291.84
Median	3.36	5438.50
Standard Deviation	5.20	2973.11
Number of Observations	101	101

Annual Probability = 1.01×10^{-8}

Case 17: Threshold Displacement = 0.4 m
Seed = 3
Number of Realization = 1,000,000

Statistics	Area Disrupted (%)	Time (yr)
Minimum	0.04	0.60
Maximum	20.64	9996.90
Mean	4.92	4575.55
Median	3.01	3956.50
Standard Deviation	5.04	3012.05
Number of Observations	111	111

Annual Probability = 1.11×10^{-8}

Case 18: Threshold Displacement = 0.4 m
Seed = 4
Number of Realization = 1,000,000

Statistics	Area Disrupted (%)	Time (yr)
Minimum	0.00	377.80
Maximum	24.40	9999.00
Mean	6.11	5492.10
Median	4.42	5356.70
Standard Deviation	5.85	2877.96
Number of Observations	95	95

Annual Probability = 9.50×10^{-9}

Case 19: Threshold Displacement = 0.4 m
Seed = 5
Number of Realization = 1,000,000

Statistics	Area Disrupted (%)	Time (yr)
Minimum	0.01	37.40
Maximum	23.35	9960.90
Mean	5.65	5381.89
Median	3.35	5430.80
Standard Deviation	5.88	2775.00
Number of Observations	81	81

Annual Probability = 8.10×10^{-9}

3.4. Summary of Results Using FAULTO code

Case 1: Threshold Displacement = 0.1 m
Number of Realization = 1,000,000

Statistics	Area Disrupted (%)
Minimum	0.00
Maximum	37.17
Mean	4.83
Median	3.46
Standard Deviation	4.54
Number of Observations	885

Case 2: Threshold Displacement = 0.1 m
Number of Realization = 1,000,000

Statistics	Area Disrupted (%)
Minimum	0.00
Maximum	28.89
Mean	3.95
Median	2.34
Standard Deviation	4.59
Number of Observations	896

Case 3: Threshold Displacement = 0.2 m
Number of Realization = 1,000,000

Statistics	Area Disrupted (%)
Minimum	0.00
Maximum	46.64
Mean	5.14
Median	3.58
Standard Deviation	5.17
Number of Observations	549

Case 4: Threshold Displacement = 0.2 m
Number of Realization = 1,000,000

Statistics	Area Disrupted (%)
Minimum	0.01
Maximum	30.61
Mean	4.62
Median	3.12
Standard Deviation	4.47
Number of Observations	568

Case 5: Threshold Displacement = 0.2 m
Number of Realization = 1,000,000

Statistics	Area Disrupted (%)
Minimum	0.01
Maximum	52.10
Mean	5.32
Median	4.10
Standard Deviation	5.00
Number of Observations	546

Case 6: Threshold Displacement = 0.2 m
Number of Realization = 1,000,000

Statistics	Area Disrupted (%)
Minimum	0.03
Maximum	58.65
Mean	4.93
Median	3.45
Standard Deviation	5.23
Number of Observations	536

Case 7: Threshold Displacement = 0.3 m
Number of Realization = 1,000,000

Statistics	Area Disrupted (%)
Minimum	0.01
Maximum	37.17
Mean	5.29
Median	3.87
Standard Deviation	4.95
Number of Observations	307

Case 8: Threshold Displacement = 0.3 m
Number of Realization = 1,000,000

Statistics	Area Disrupted (%)
Minimum	0.00
Maximum	28.89
Mean	3.95
Median	2.34
Standard Deviation	4.59
Number of Observations	896

Case 9: Threshold Displacement = 0.4 m
Number of Realization = 1,000,000

Statistics	Area Disrupted (%)
Minimum	0.02
Maximum	23.48
Mean	5.04
Median	3.67
Standard Deviation	4.60
Number of Observations	114

Case 10: Threshold Displacement = 0.4 m
Number of Realization = 1,000,000

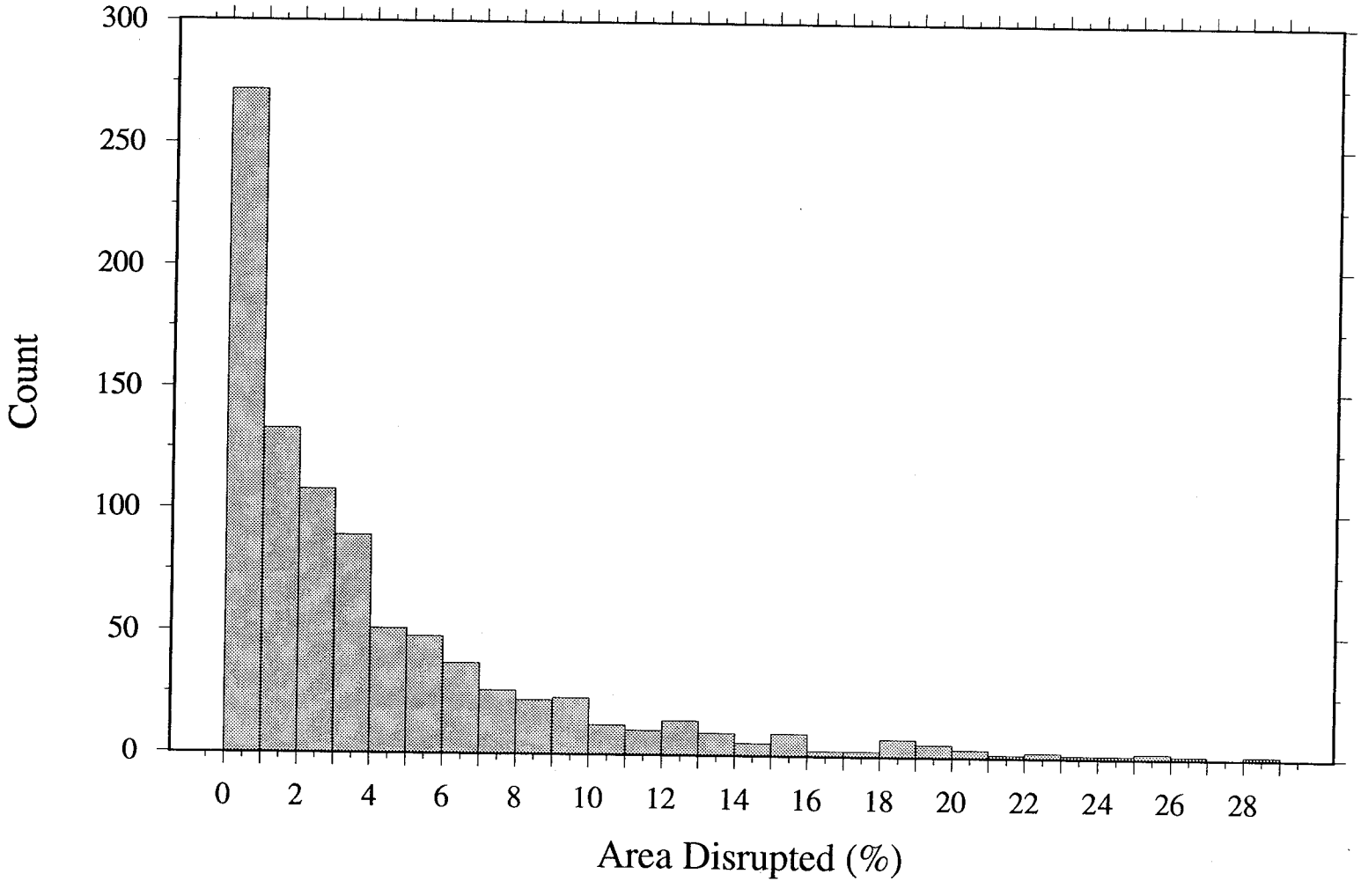
Statistics	Area Disrupted (%)
Minimum	0.03
Maximum	25.33
Mean	4.79
Median	3.48
Standard Deviation	4.91
Number of Observations	98

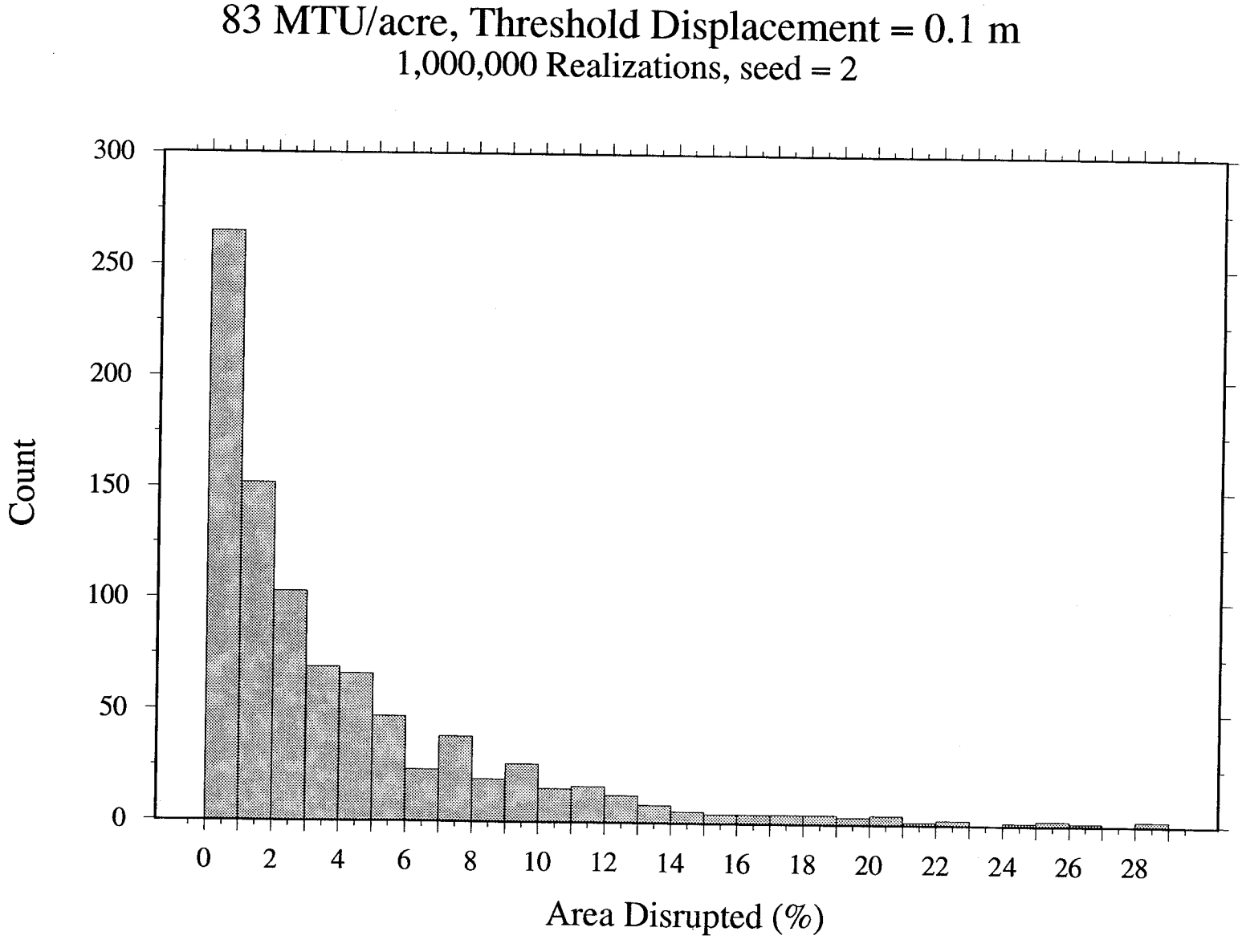
APPENDIX A

FIGURES FROM FAULTING CODE

83 MTU/acre, Threshold Displacement = 0.1 m

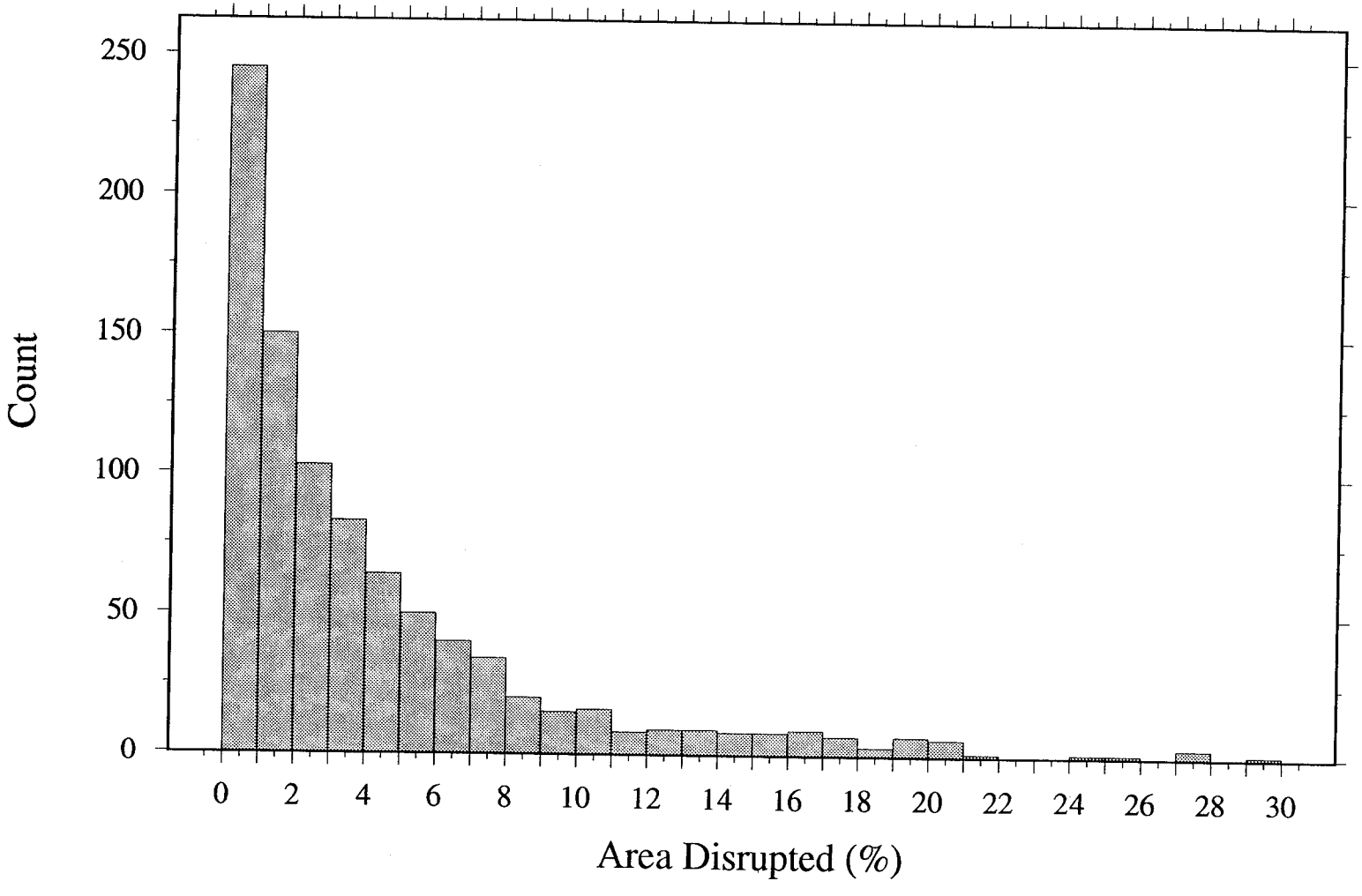
1,000,000 Realizations, seed = 1




83 MTU/acre, Threshold Displacement = 0.1 m
1,000,000 Realizations, seed = 2
Count
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
Area Disrupted (%)

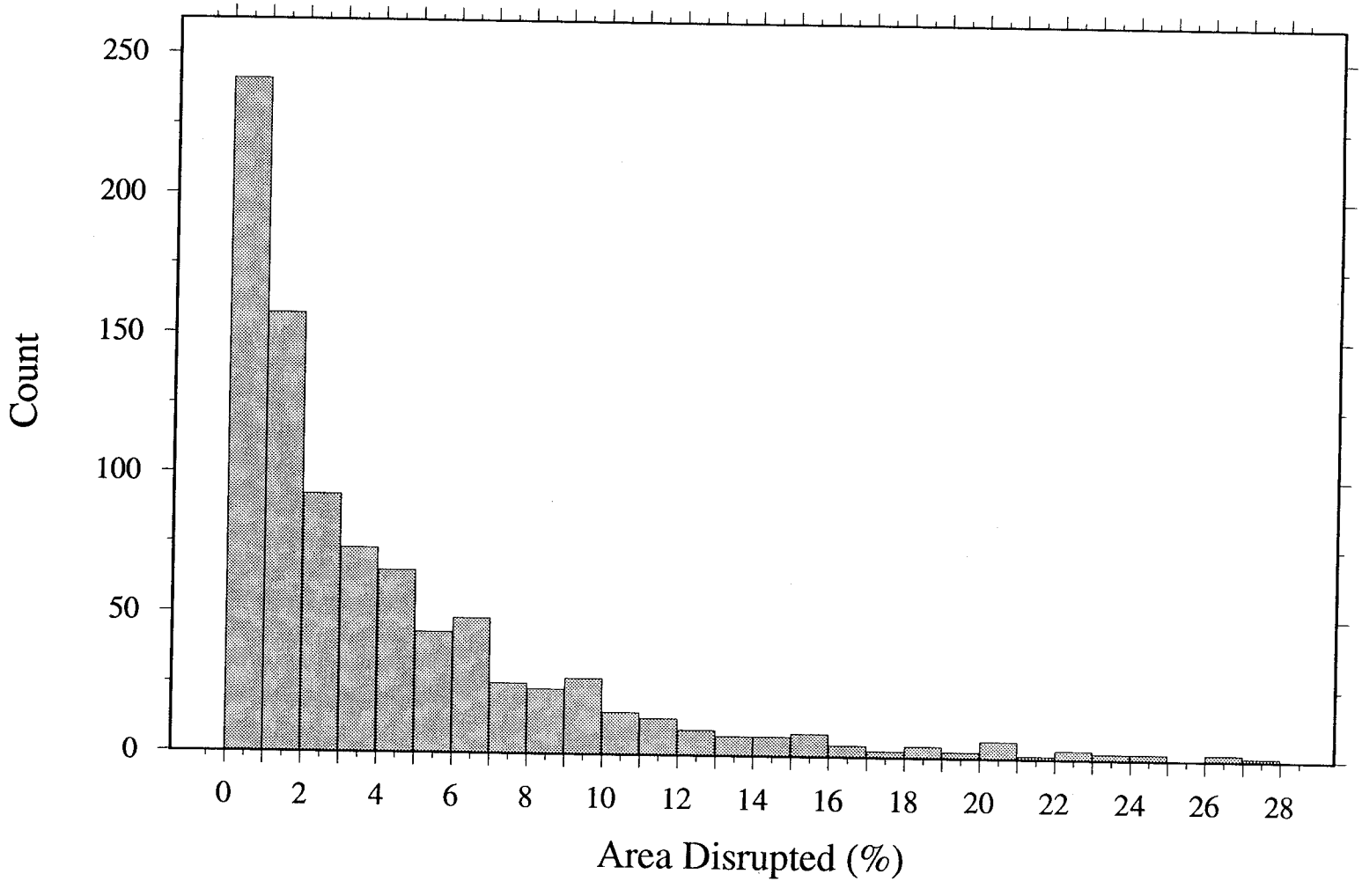
83 MTU/acre, Threshold Displacement = 0.1 m

1,000,000 Realizations, seed = 3



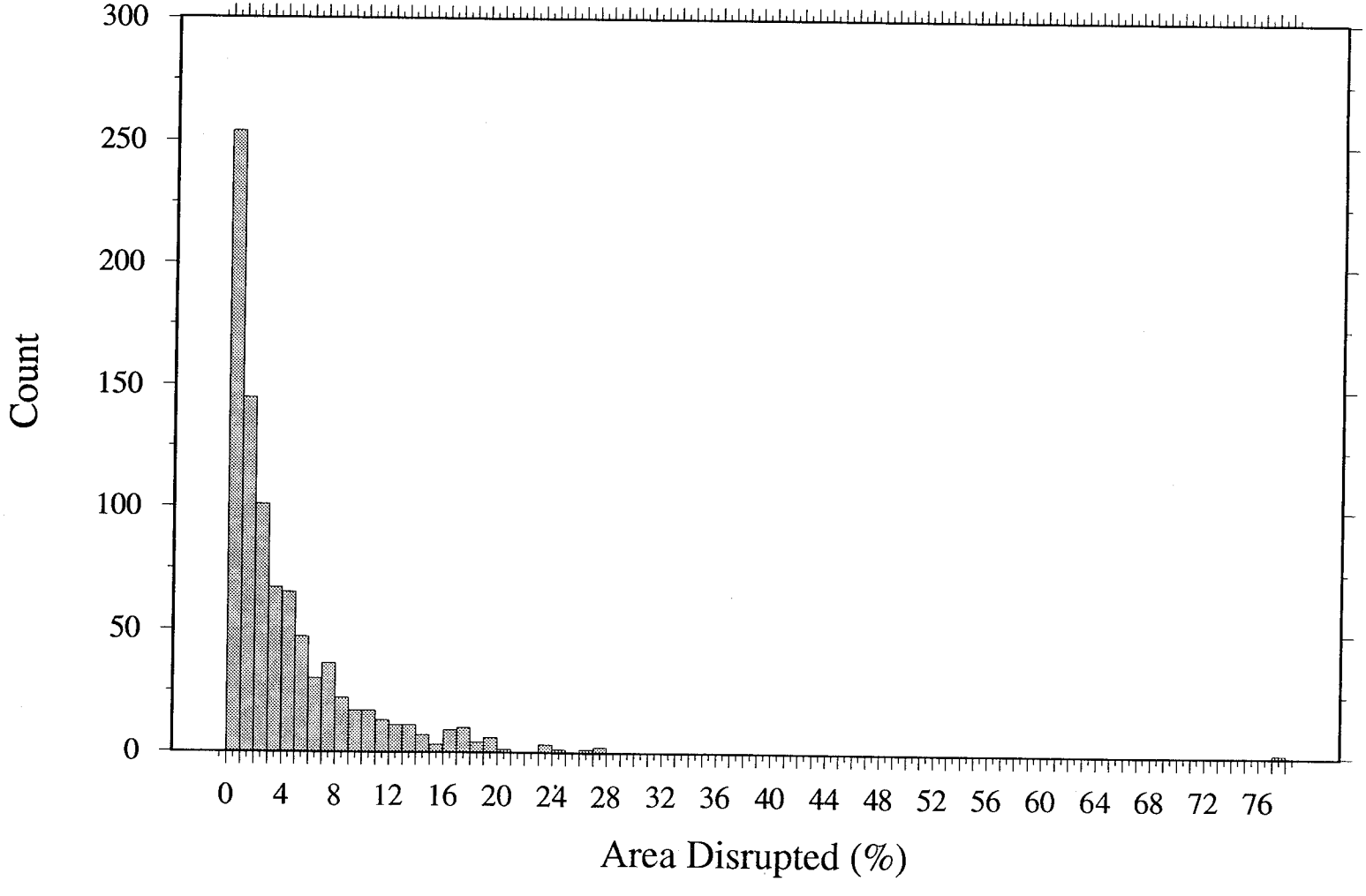
83 MTU/acre, Threshold Displacement = 0.1 m

1,000,000 Realizations, seed = 4



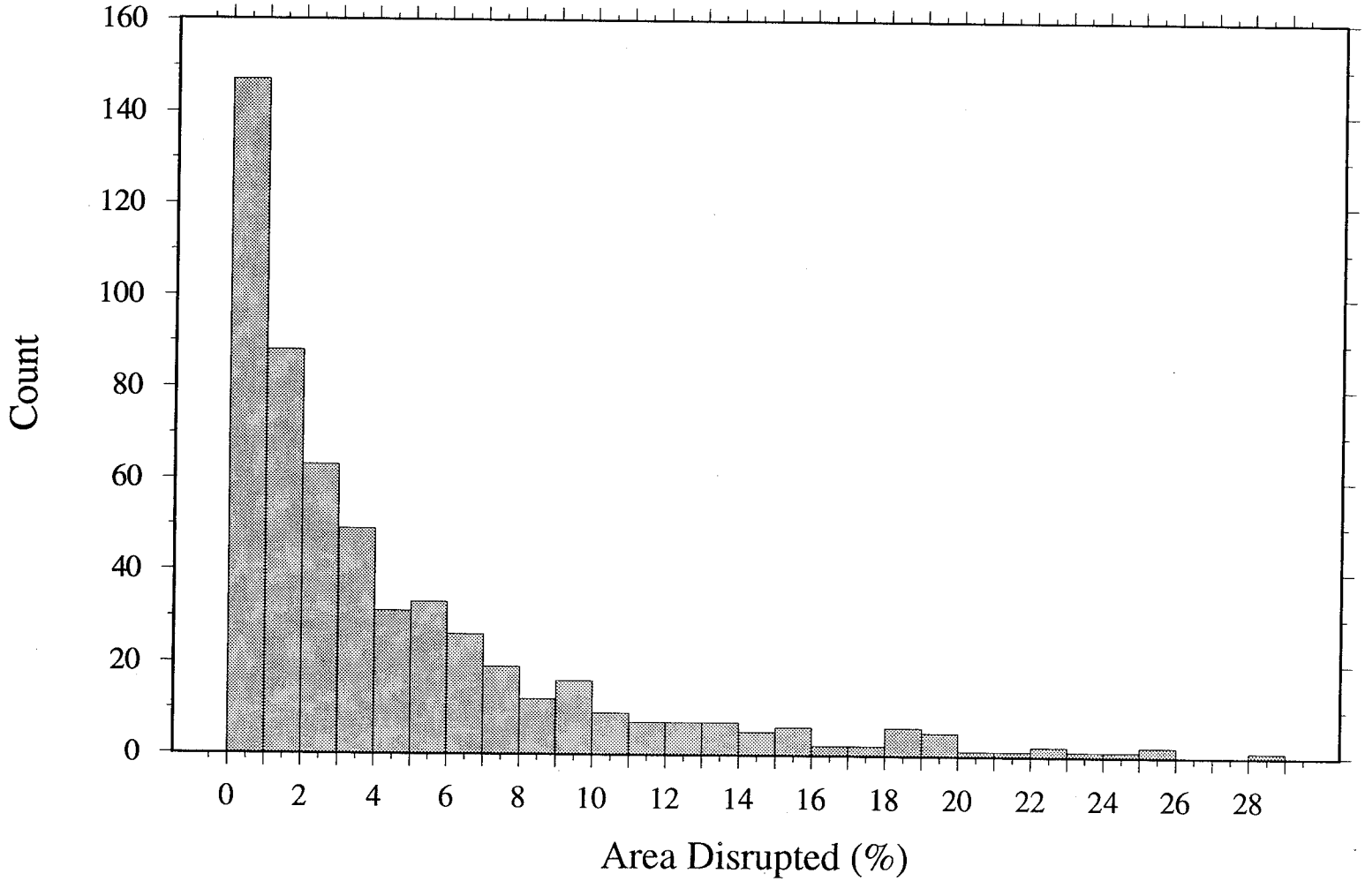
83 MTU/acre, Threshold Displacement = 0.1 m

1,000,000 Realizations, seed = 5



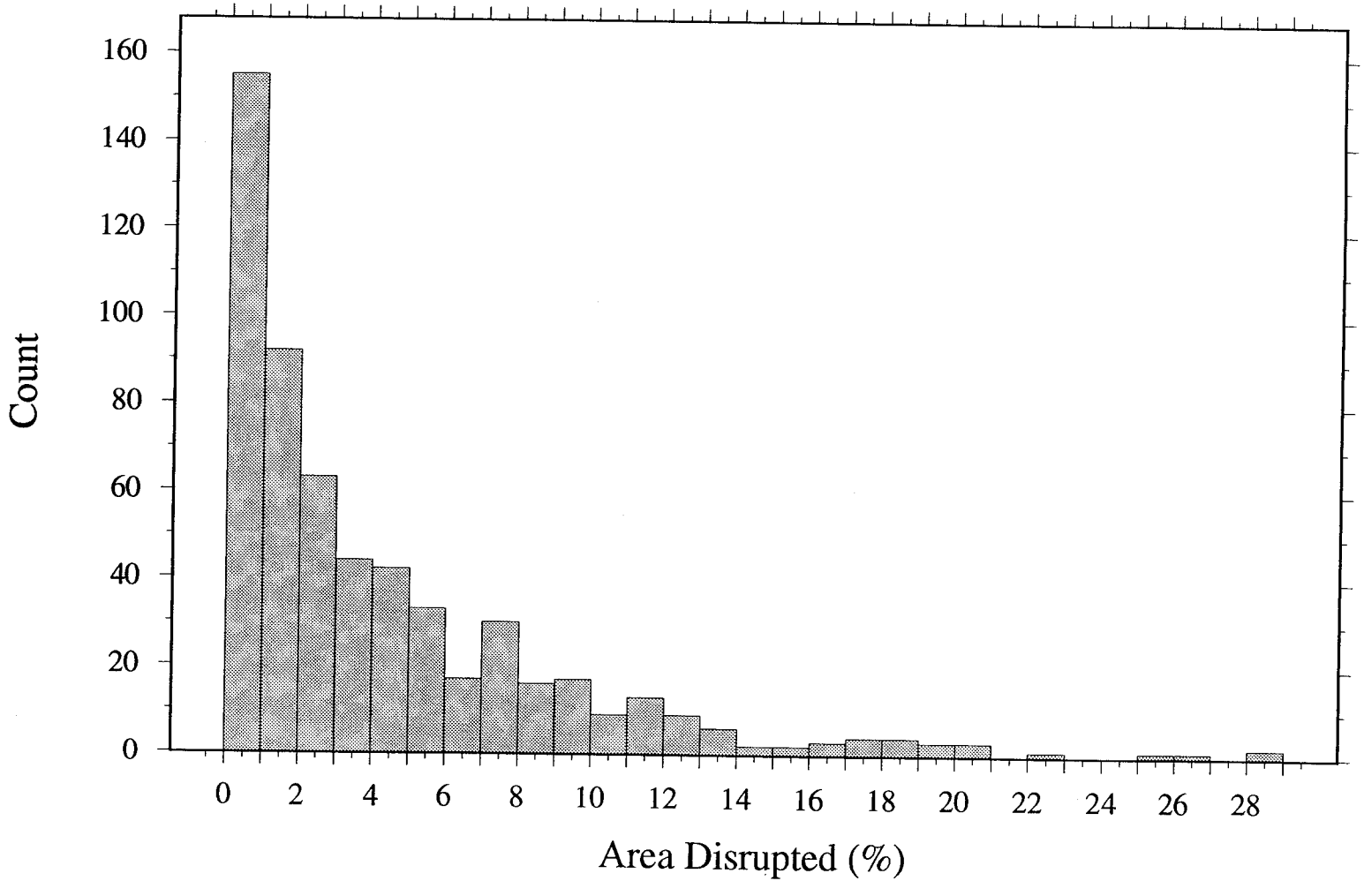
83 MTU/acre, Threshold Displacement = 0.2 m

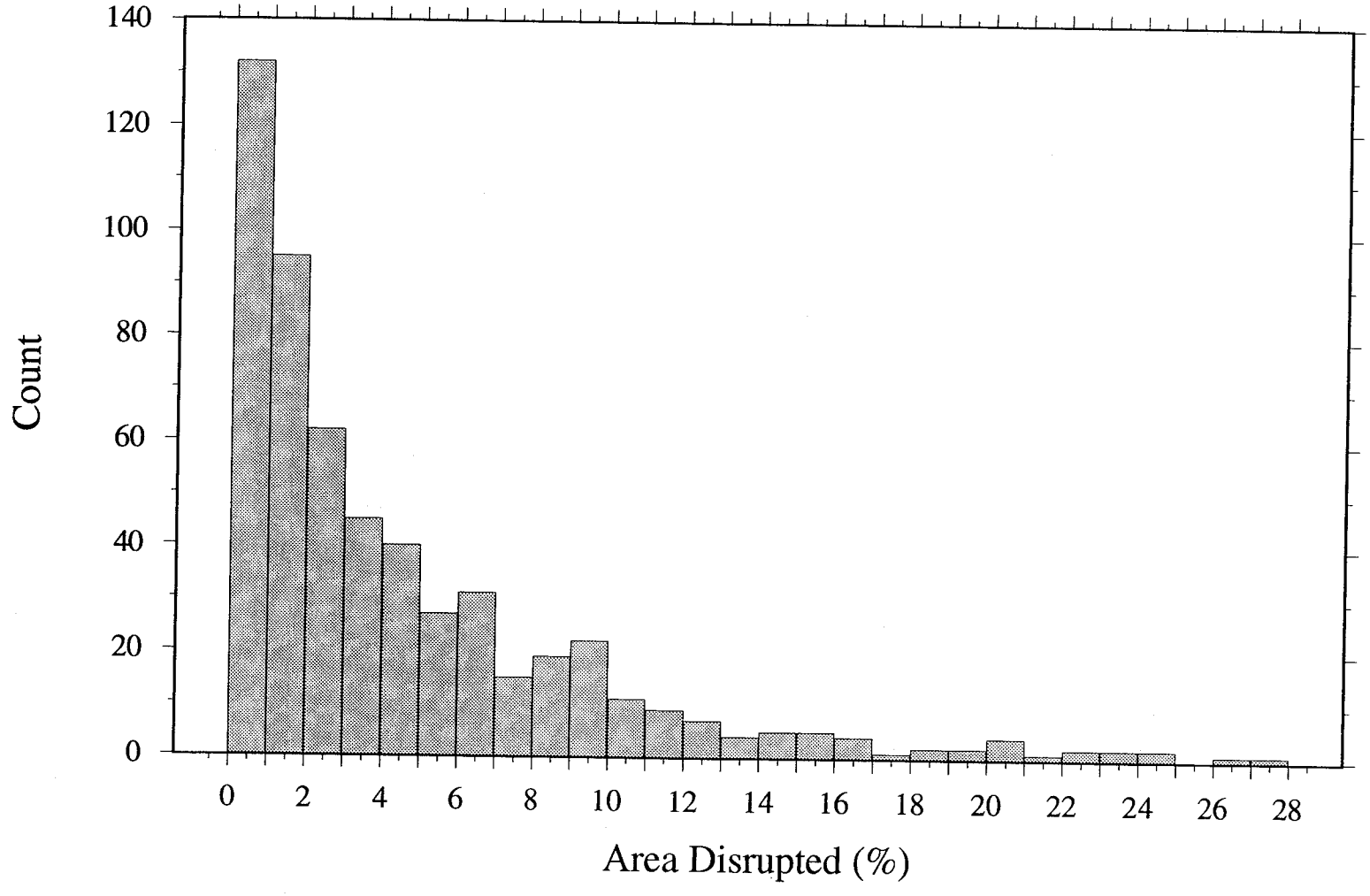
1,000,000 Realizations, seed = 1

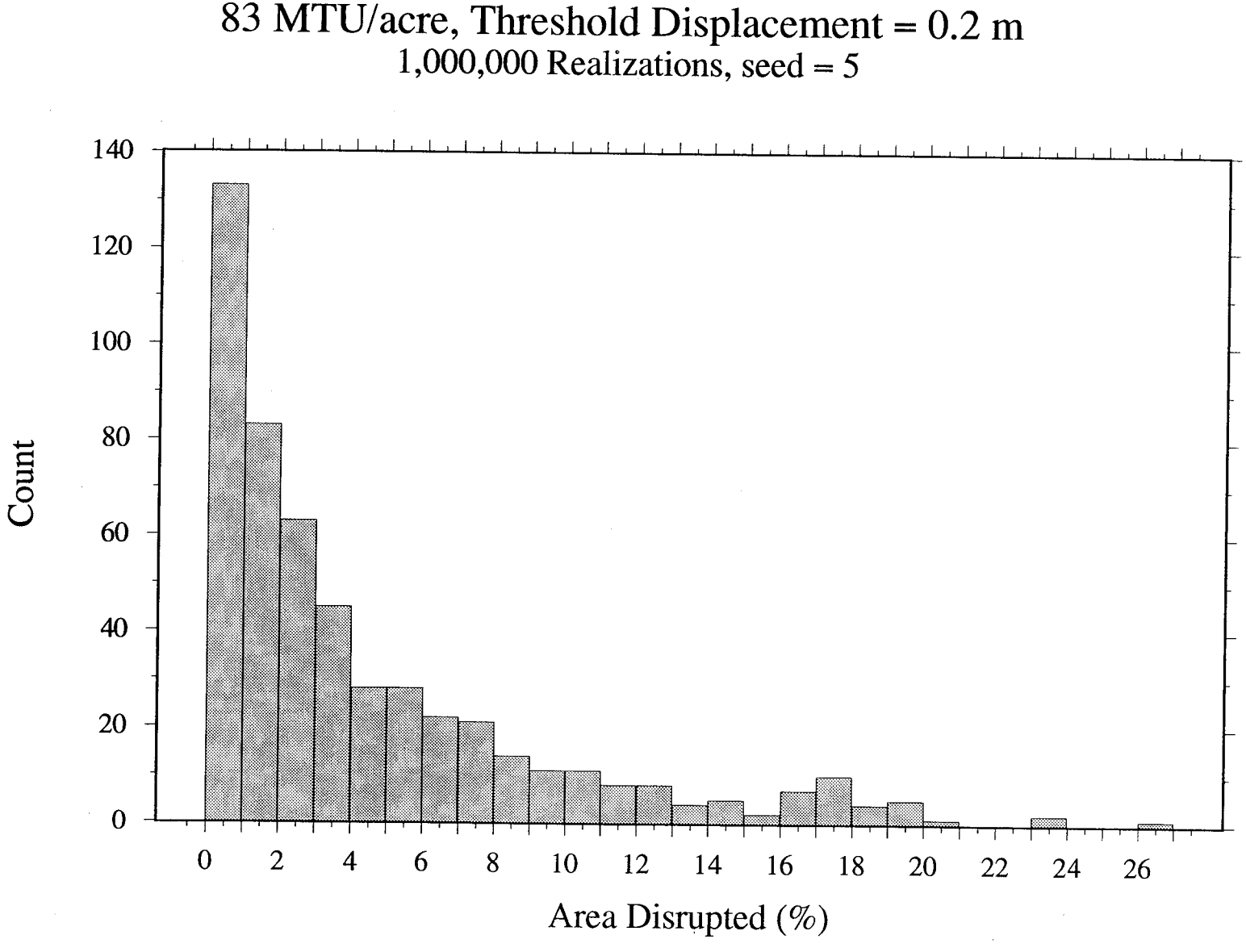


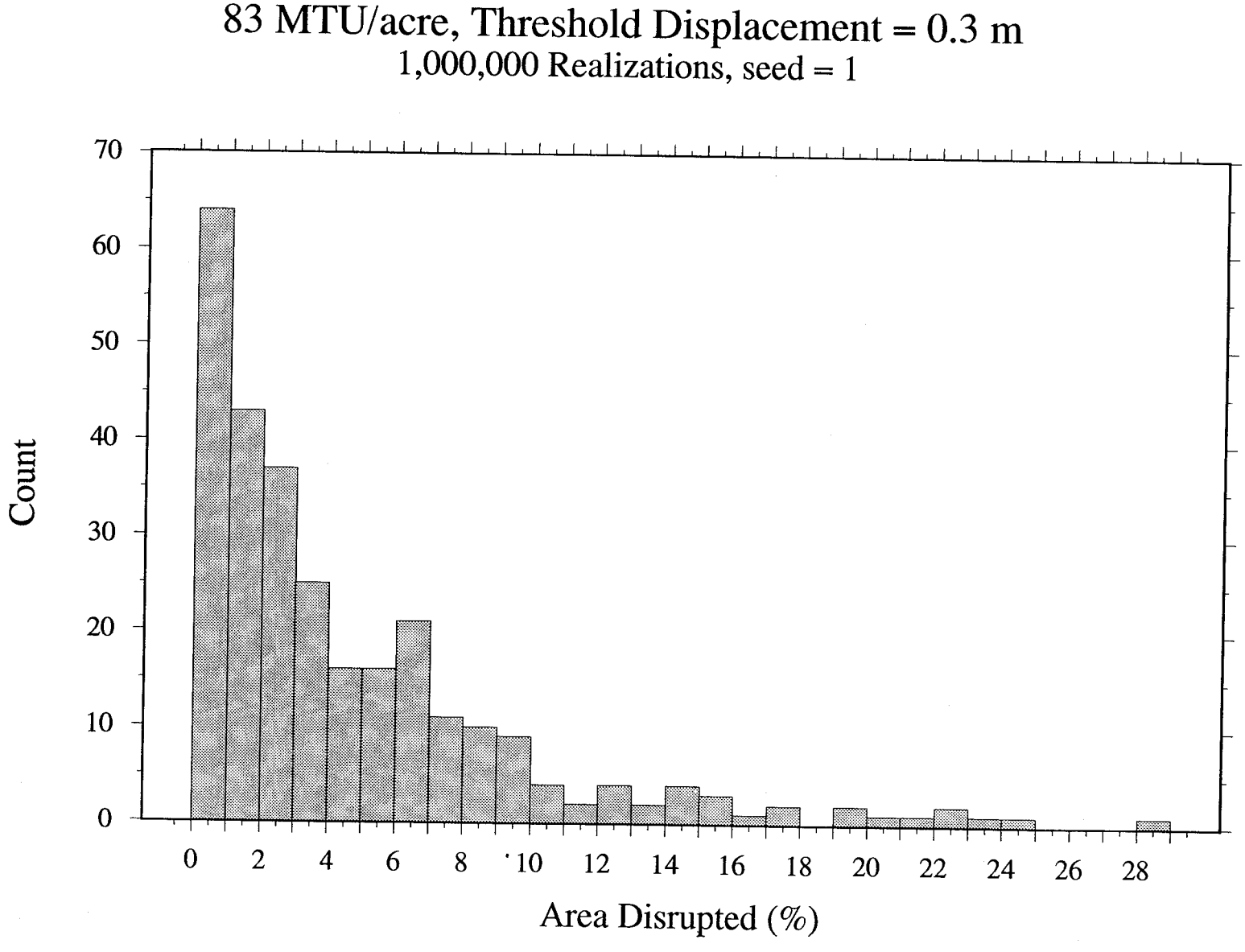
83 MTU/acre, Threshold Displacement = 0.2 m

1,000,000 Realizations, seed = 2



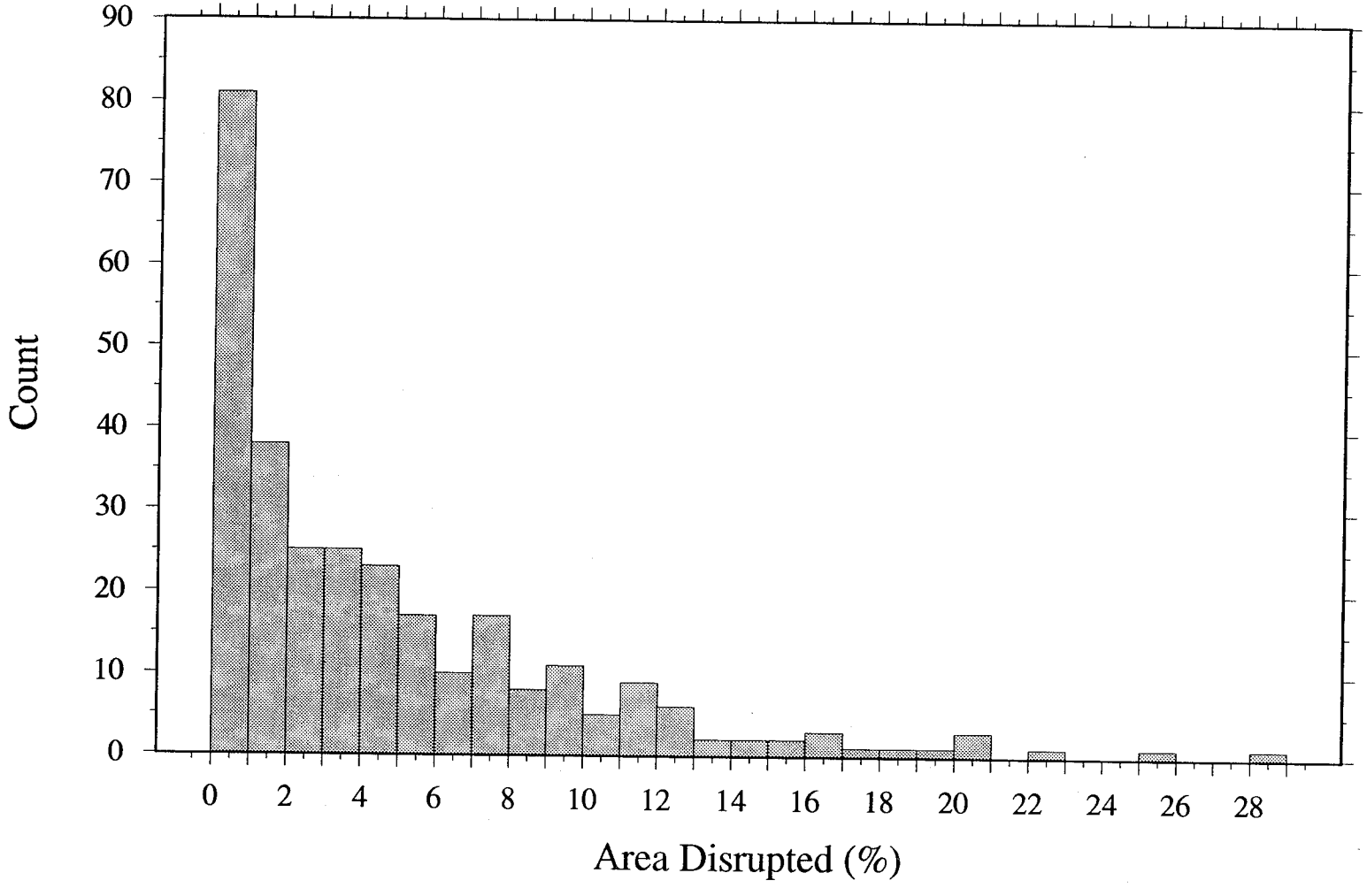

83 MTU/acre, Threshold Displacement = 0.2 m
1,000,000 Realizations, seed = 4
Count
140
120
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
Area Disrupted (%)


83 MTU/acre, Threshold Displacement = 0.2 m
1,000,000 Realizations, seed = 5
Count
140
120
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
Area Disrupted (%)


83 MTU/acre, Threshold Displacement = 0.3 m
1,000,000 Realizations, seed = 1
Count
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
Area Disrupted (%)

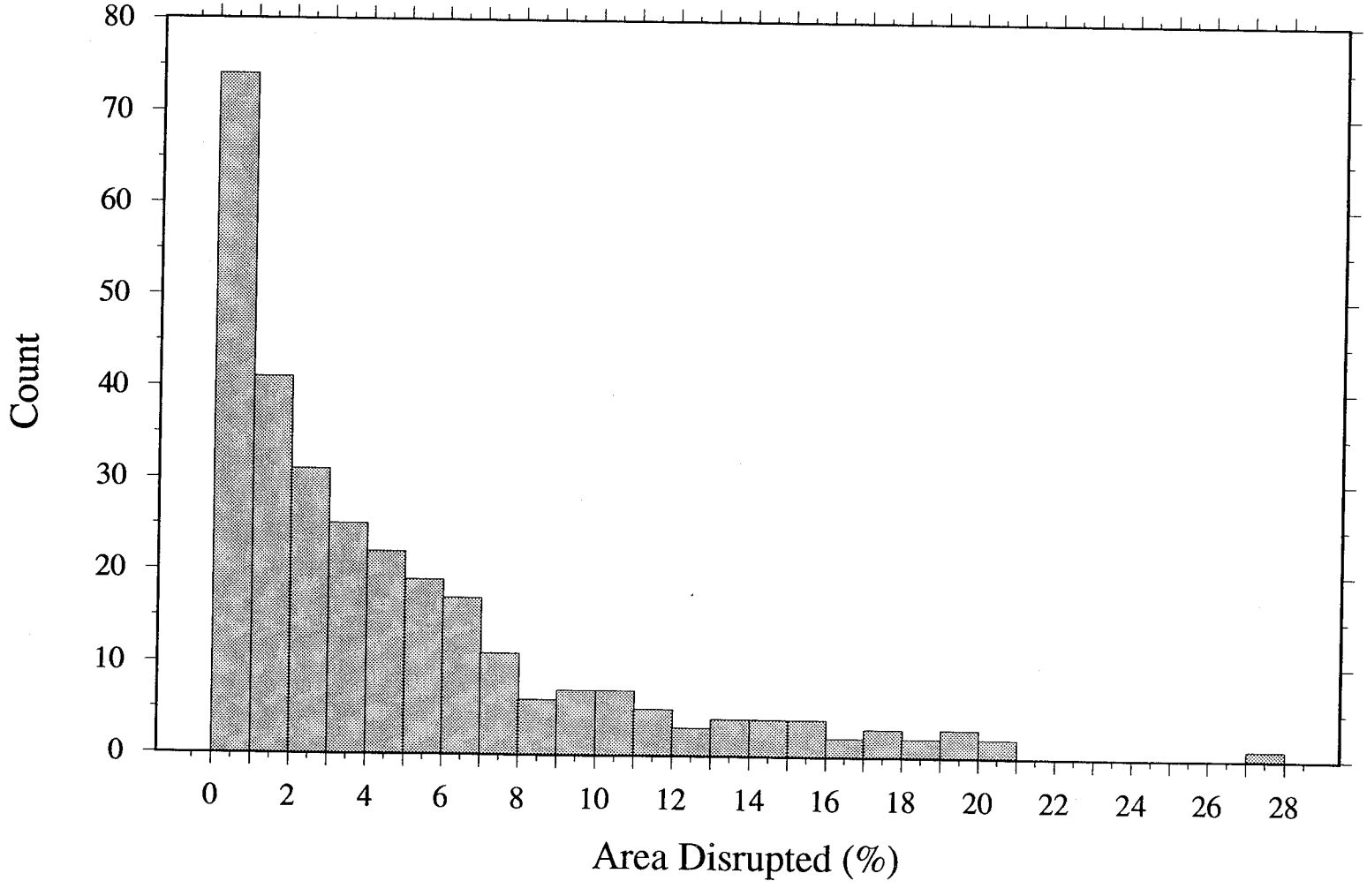
83 MTU/acre, Threshold Displacement = 0.3 m

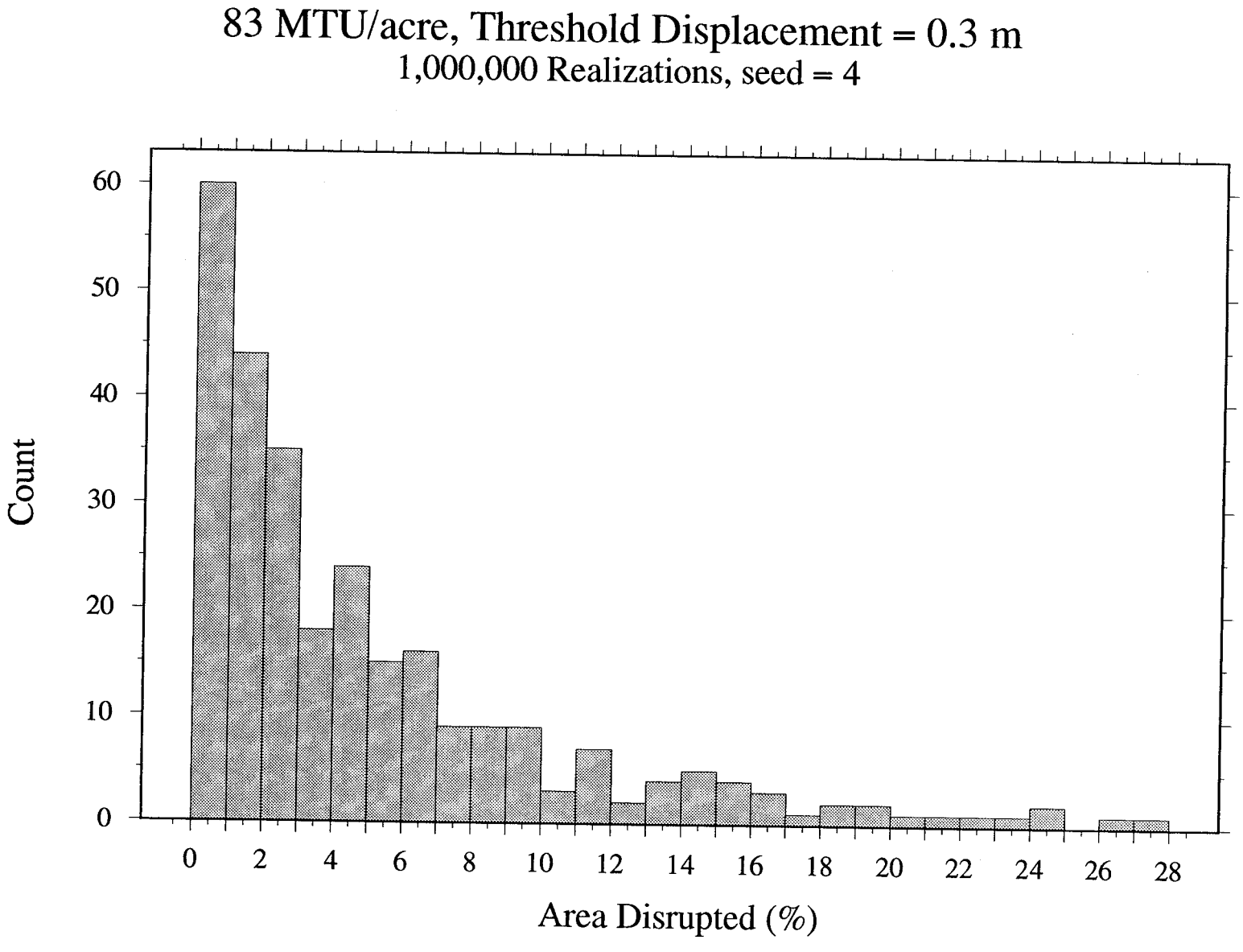
1,000,000 Realizations, seed = 2

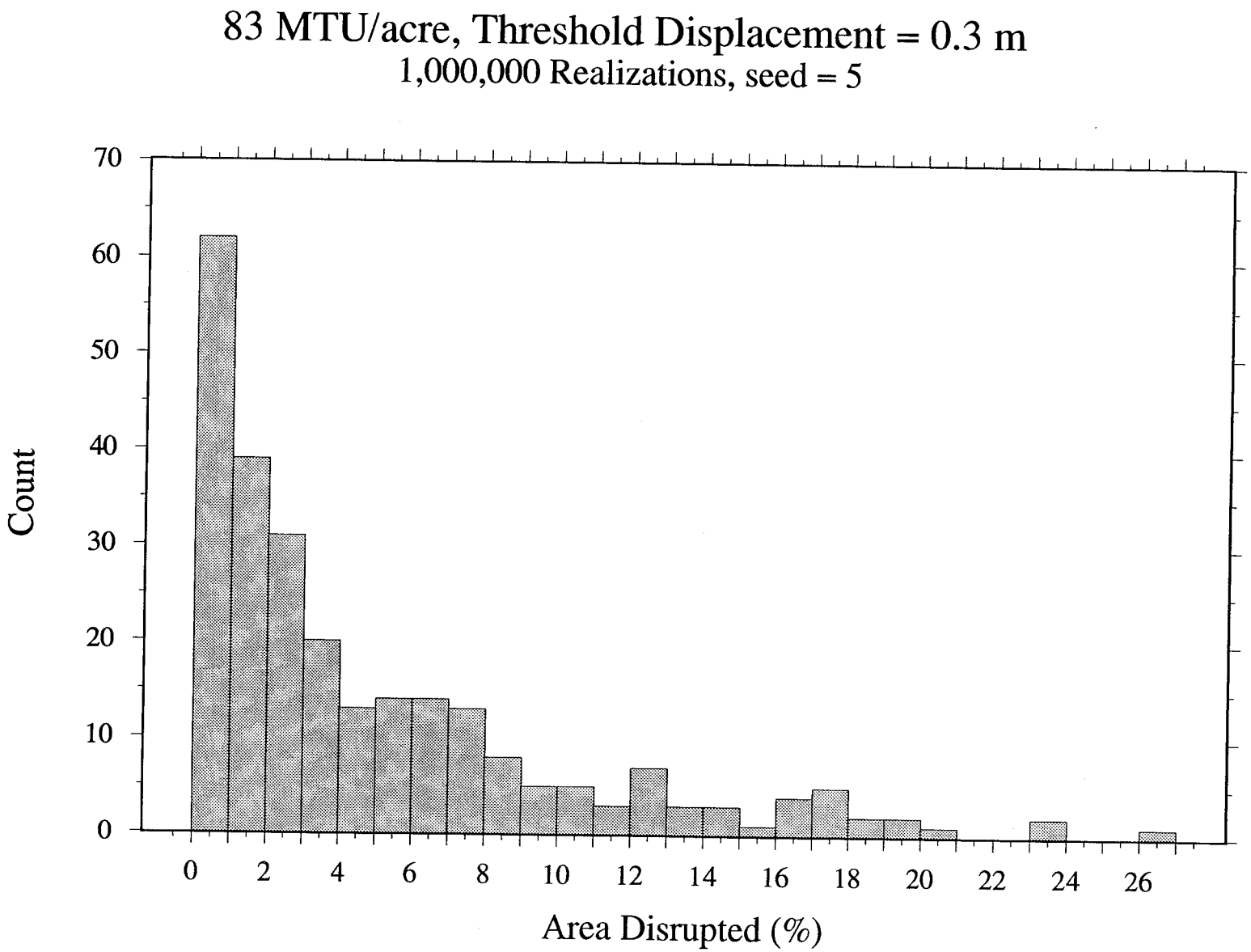


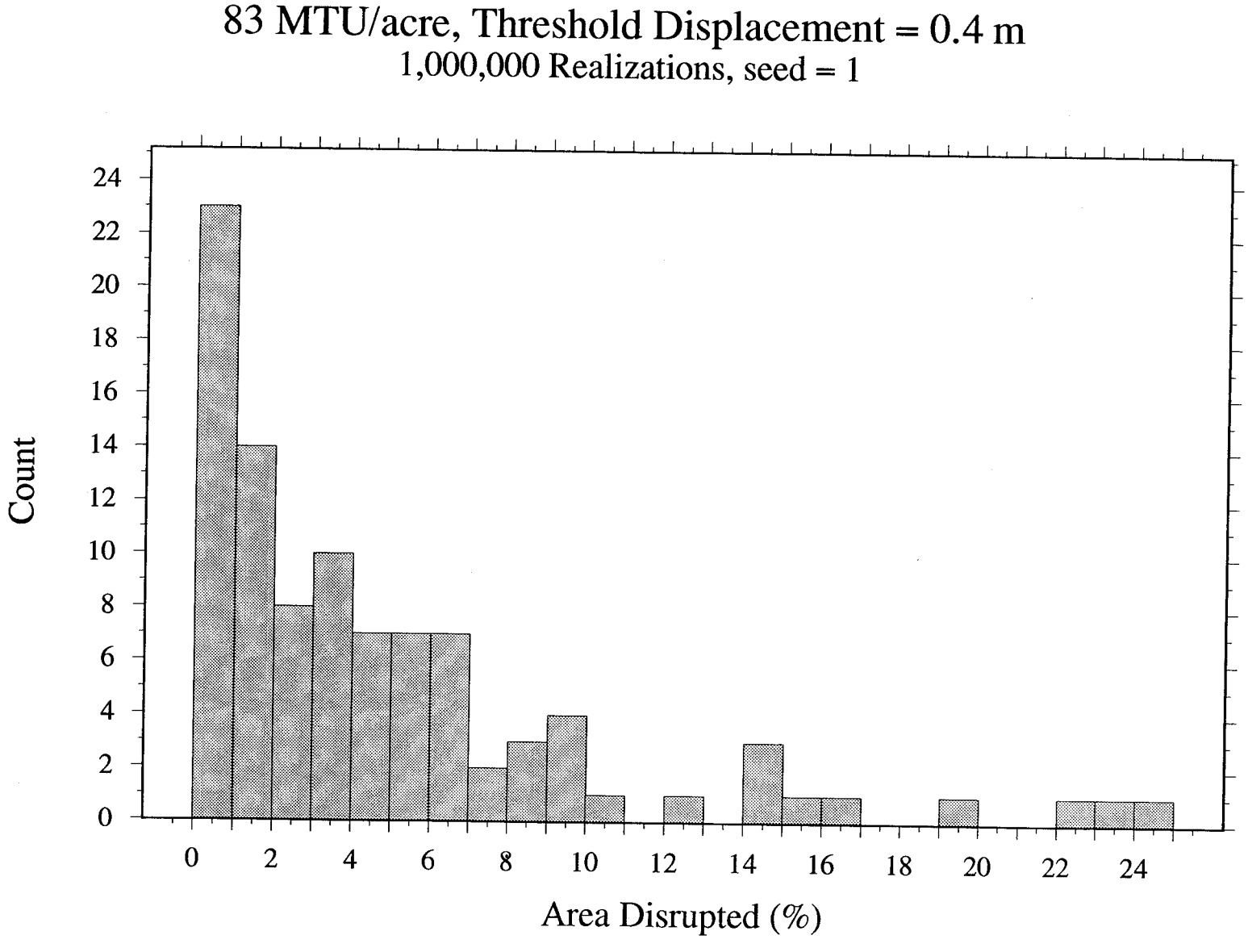
83 MTU/acre, Threshold Displacement = 0.3 m

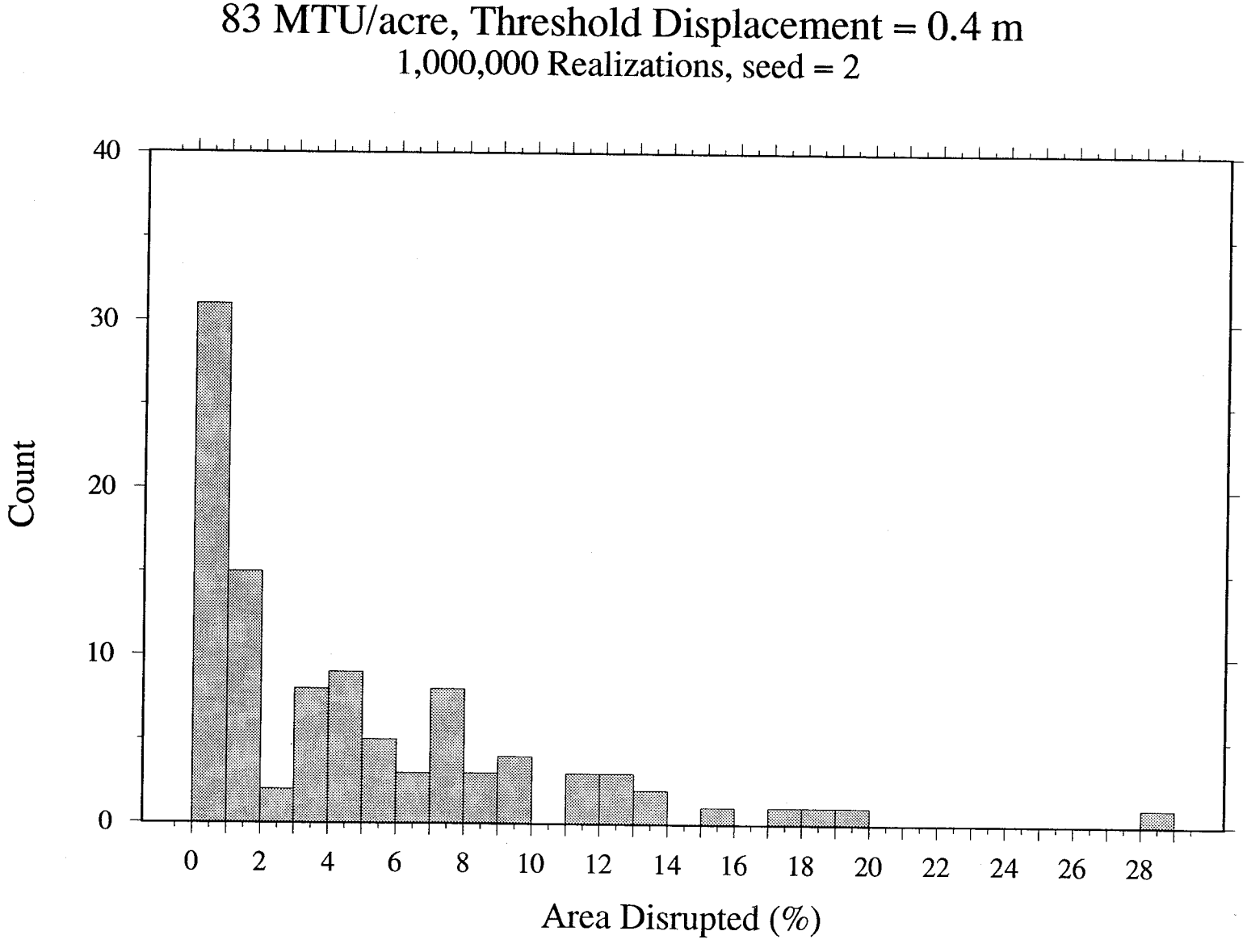
1,000,000 Realizations, seed = 3

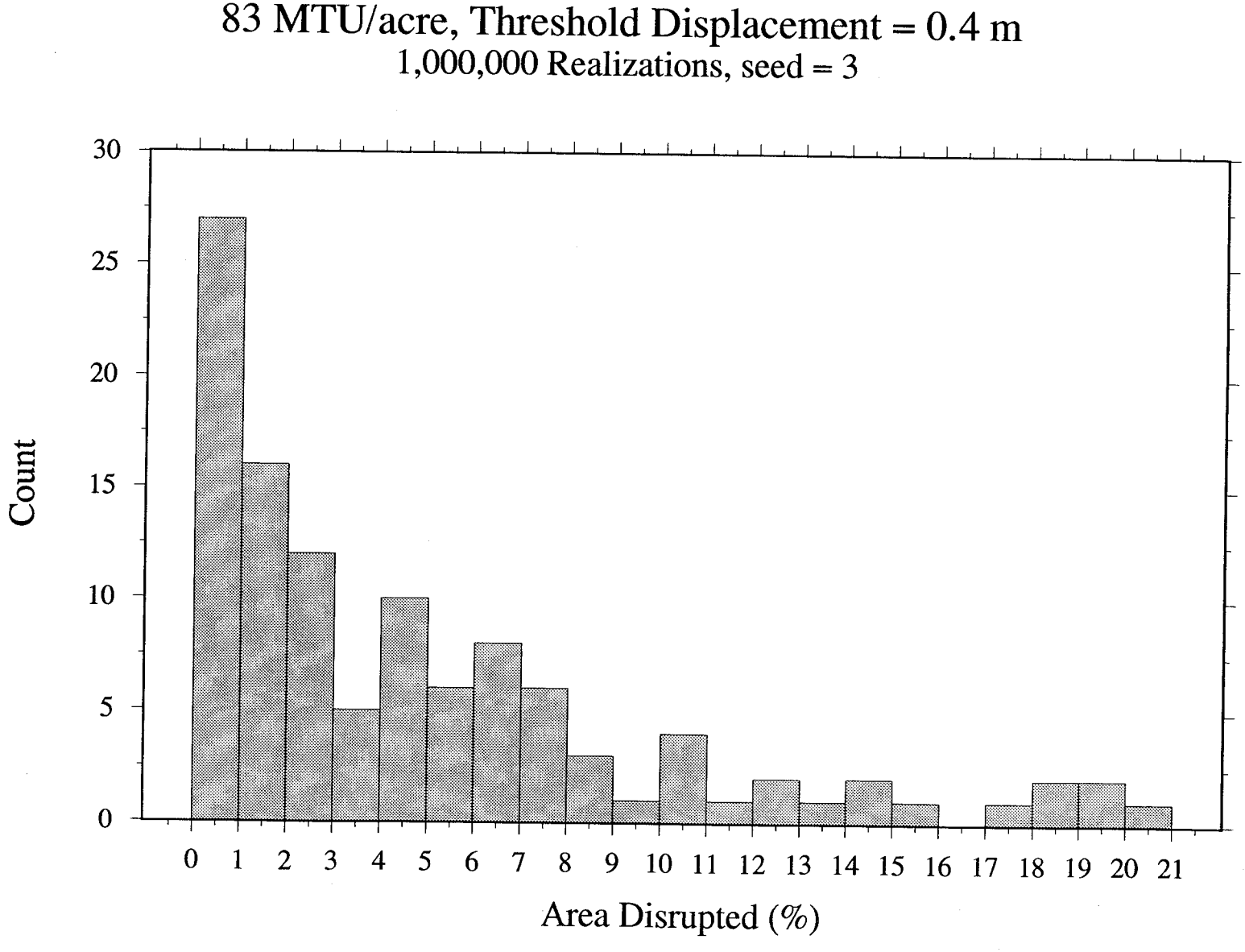



83 MTU/acre, Threshold Displacement = 0.3 m
1,000,000 Realizations, seed = 4
Count
0
10
20
30
40
50
60
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
Area Disrupted (%)


83 MTU/acre, Threshold Displacement = 0.3 m
1,000,000 Realizations, seed = 5
Count
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
Area Disrupted (%)

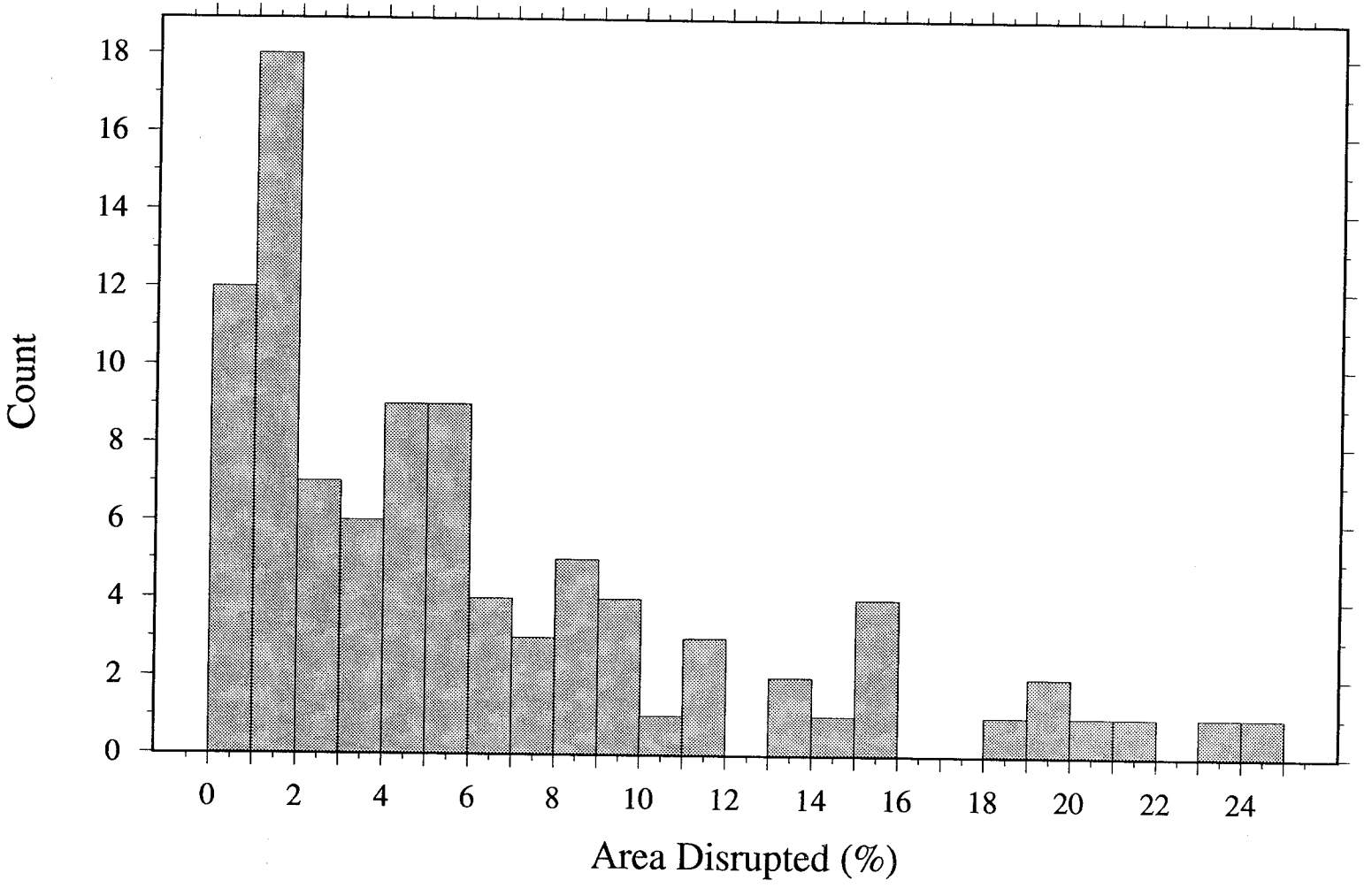

83 MTU/acre, Threshold Displacement = 0.4 m
1,000,000 Realizations, seed = 1
Count
0
2
4
6
8
10
12
14
16
18
20
22
24
Area Disrupted (%)


83 MTU/acre, Threshold Displacement = 0.4 m
1,000,000 Realizations, seed = 2
Count
40
30
20
10
0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
Area Disrupted (%)


83 MTU/acre, Threshold Displacement = 0.4 m
1,000,000 Realizations, seed = 3
Count
0
5
10
15
20
25
30
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Area Disrupted (%)

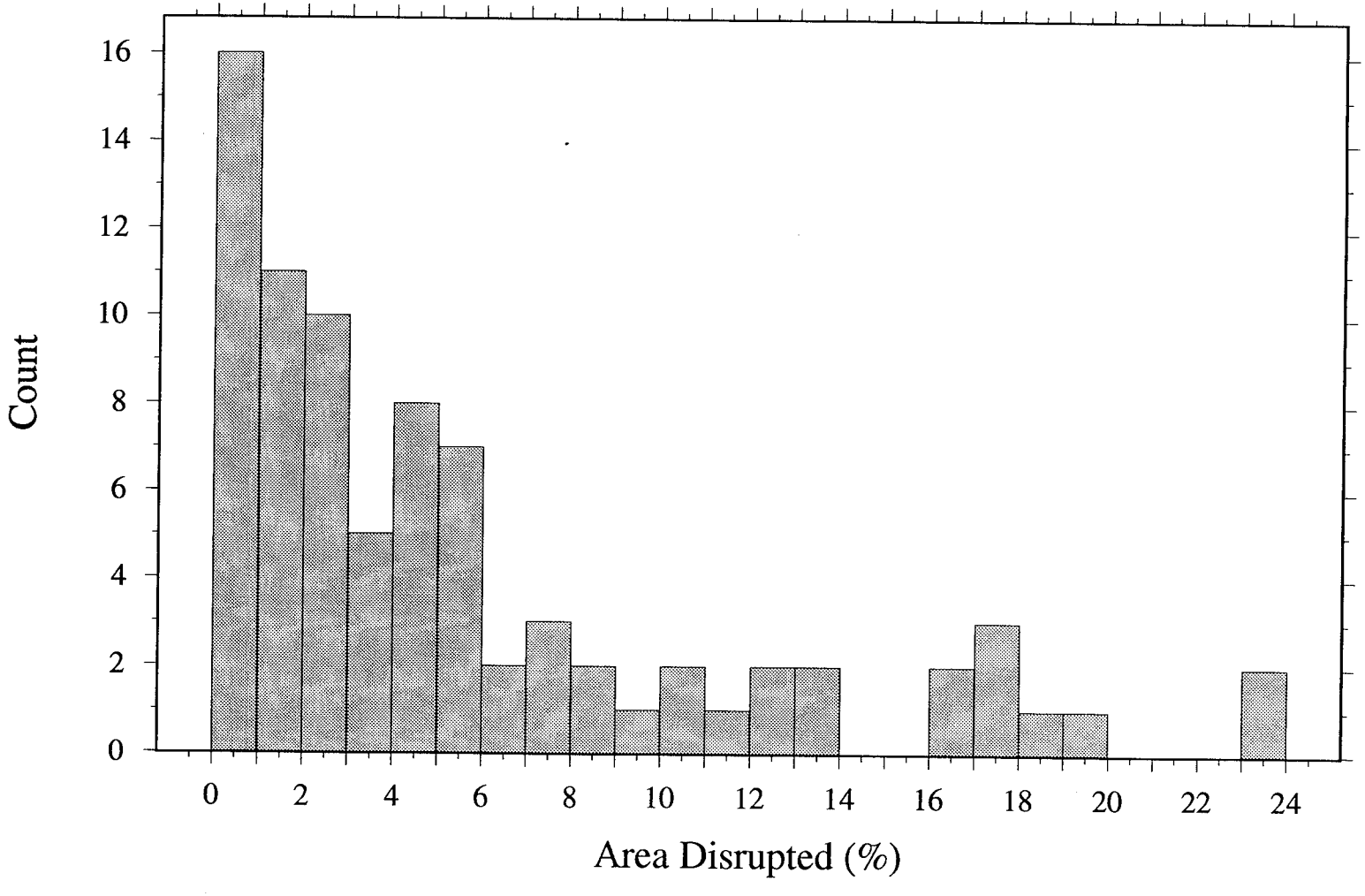
83 MTU/acre, Threshold Displacement = 0.4 m

1,000,000 Realizations, seed = 4



83 MTU/acre, Threshold Displacement = 0.4 m

1,000,000 Realizations, seed = 5

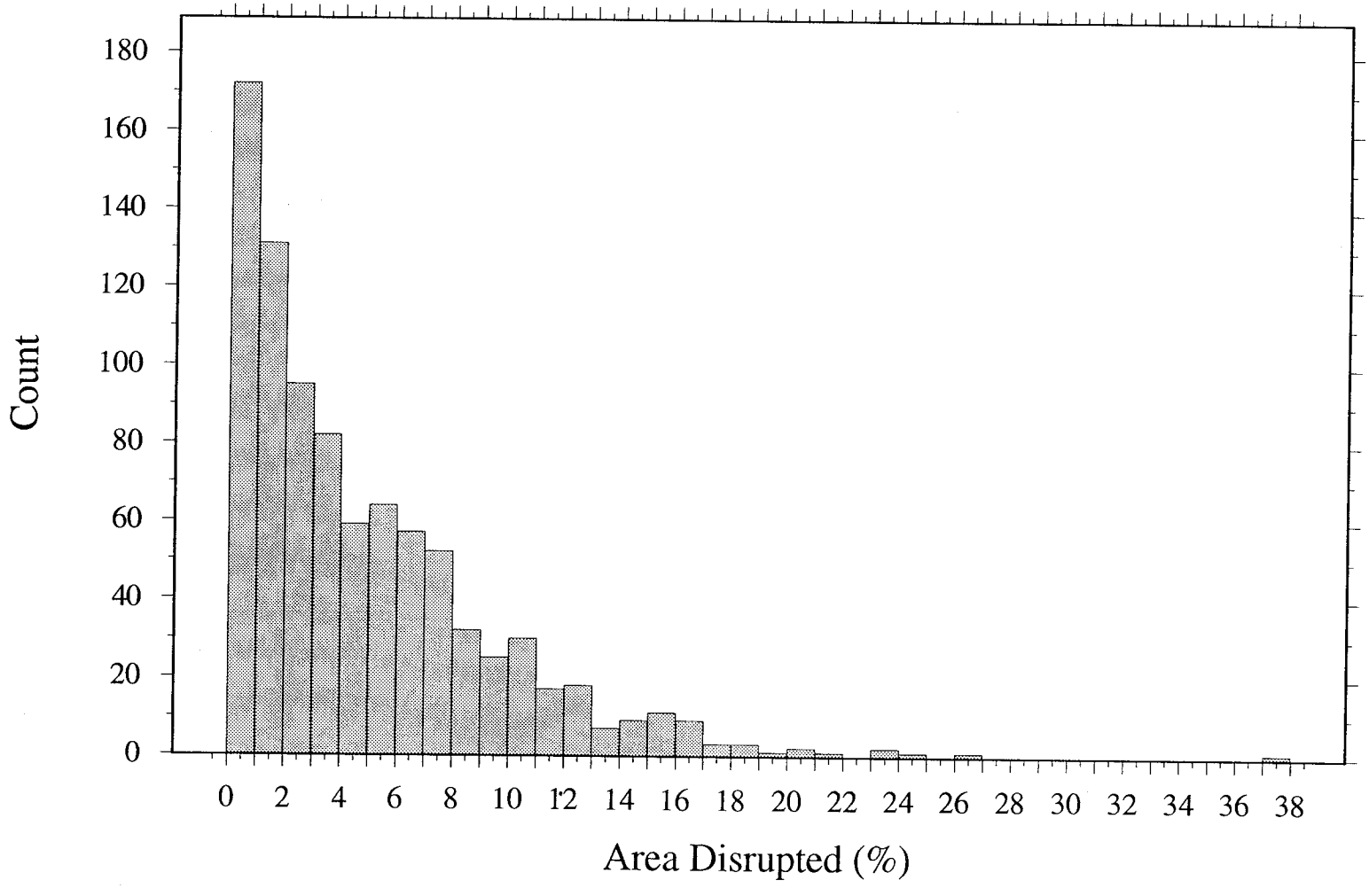


APPENDIX B

FIGURES FROM FAULTO MODULE

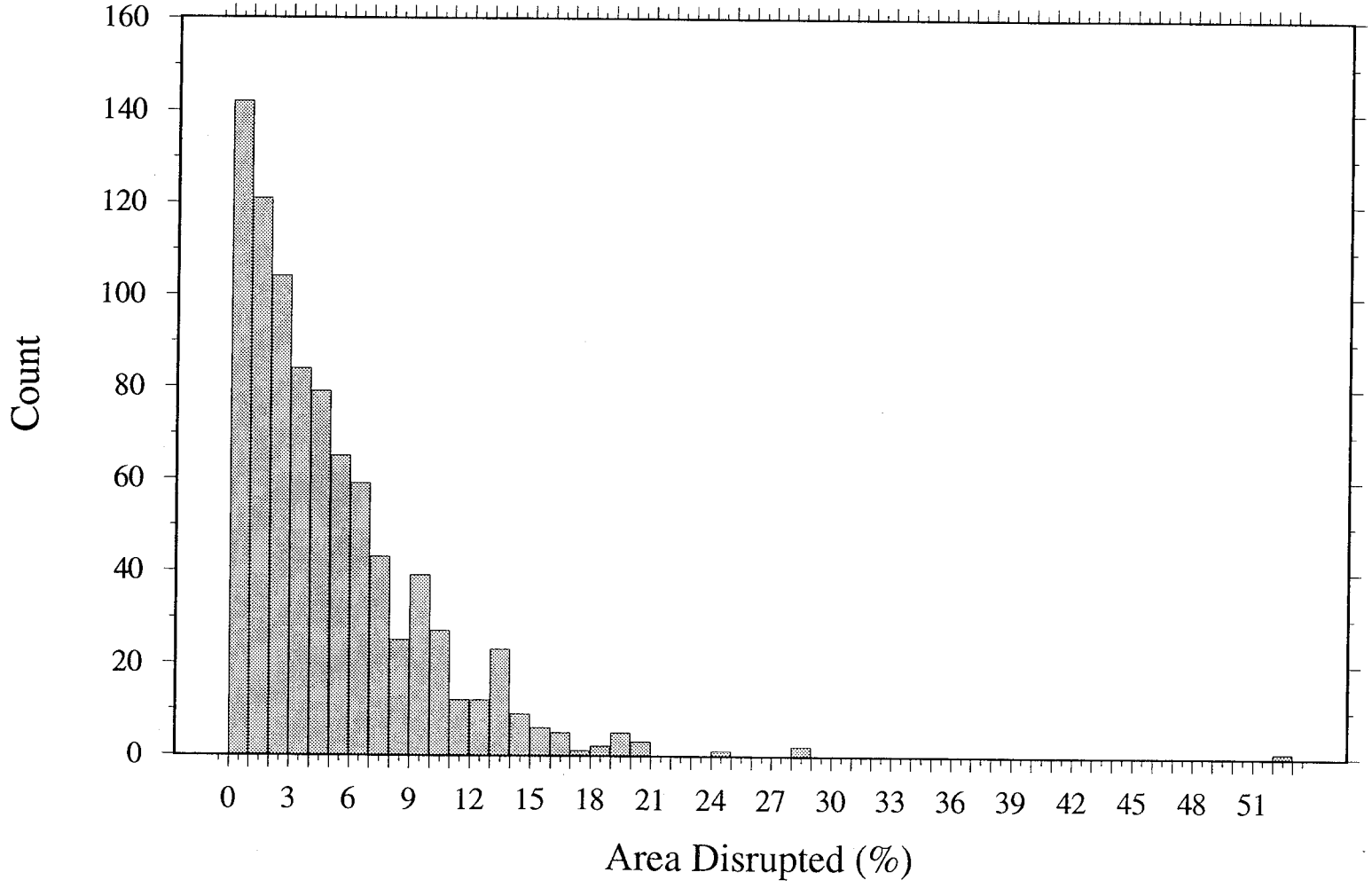
83 MTU/acre, Threshold Displacement = 0.1 m (FAULTO)

1,000,000 Realizations, Case = 1



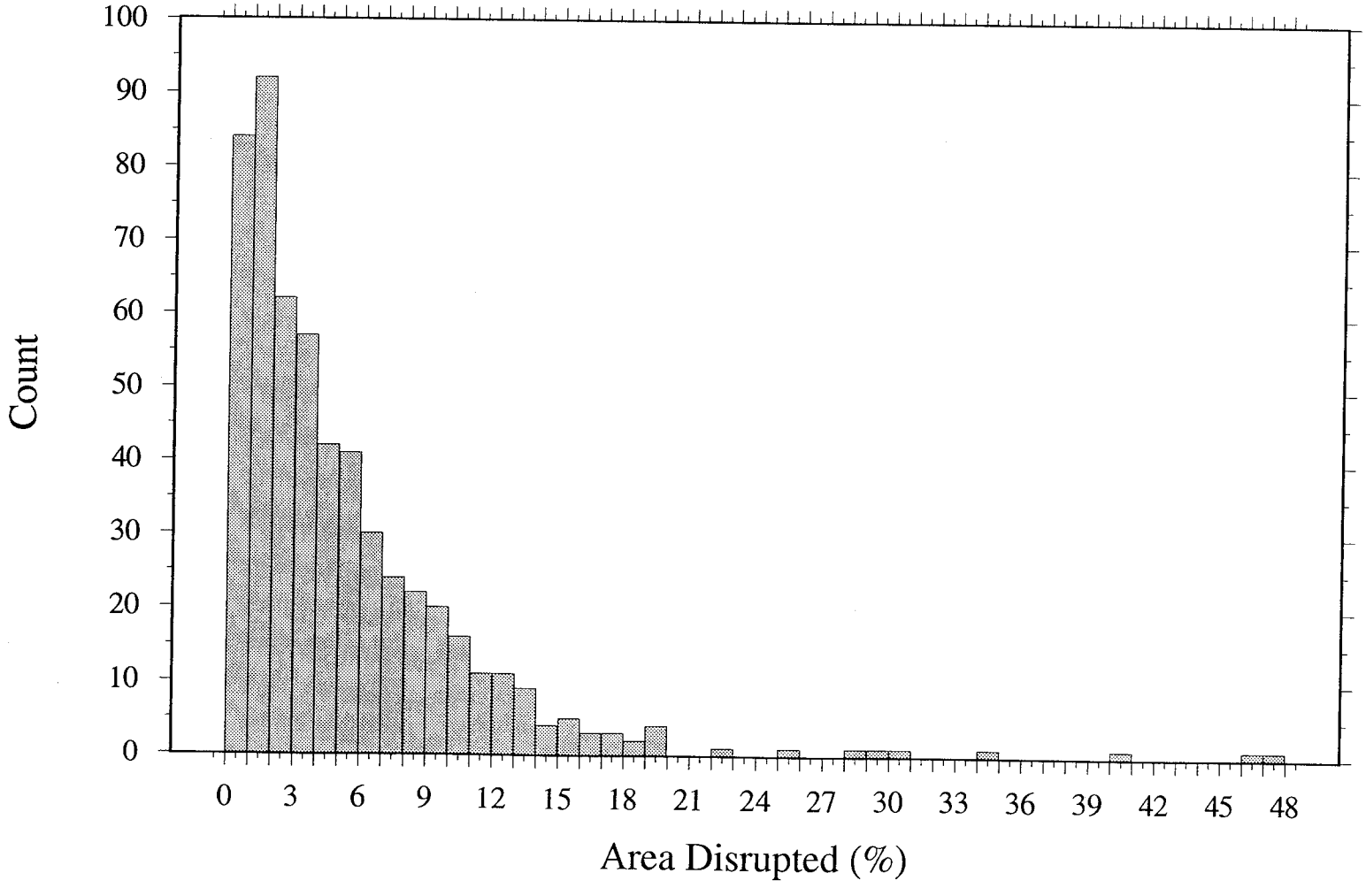
83 MTU/acre, Threshold Displacement = 0.1 m (FAULTO)

1,000,000 Realizations, Case = 2



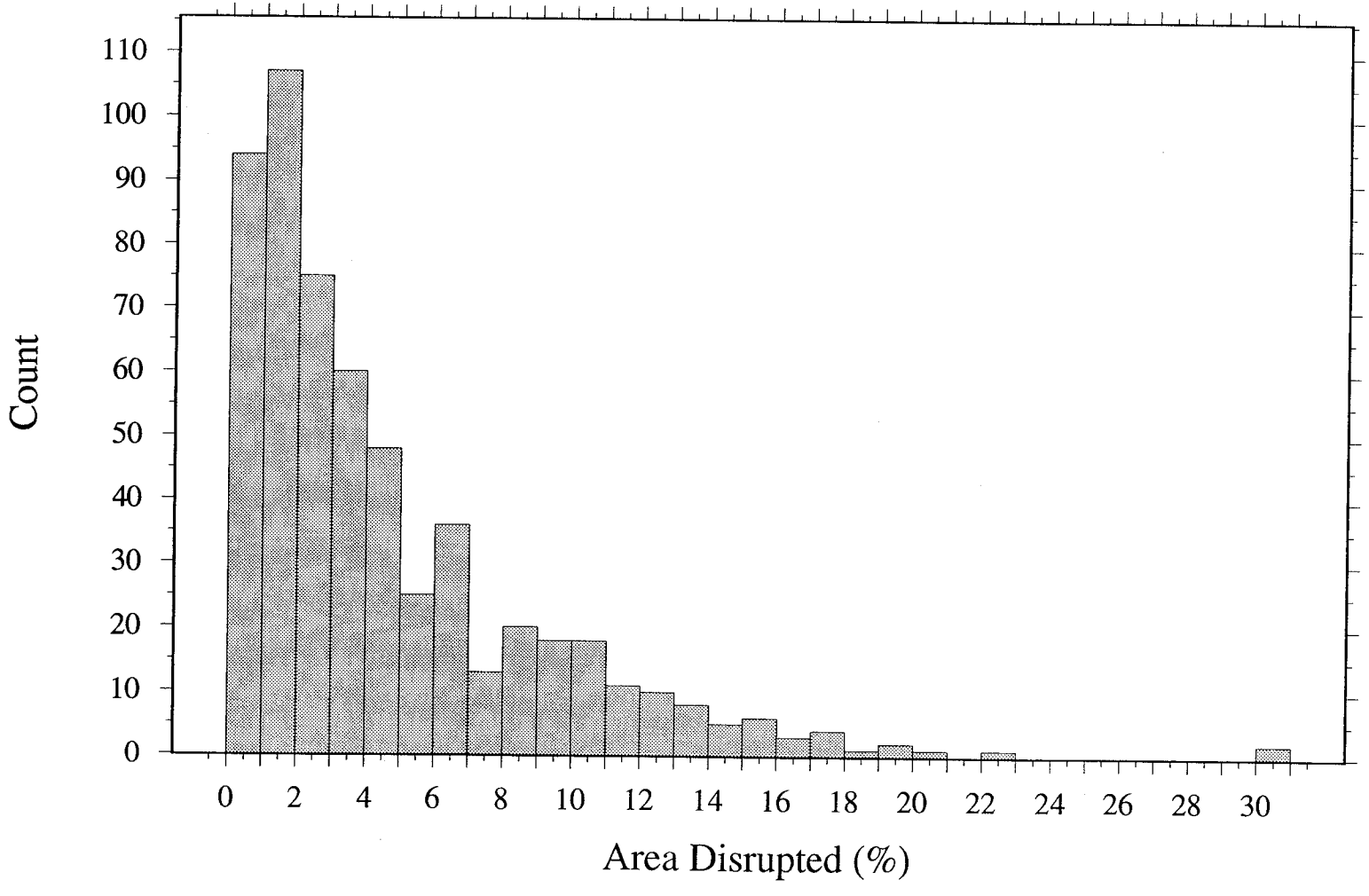
83 MTU/acre, Threshold Displacement = 0.2 m (FAULTO)

1,000,000 Realizations, Case = 1



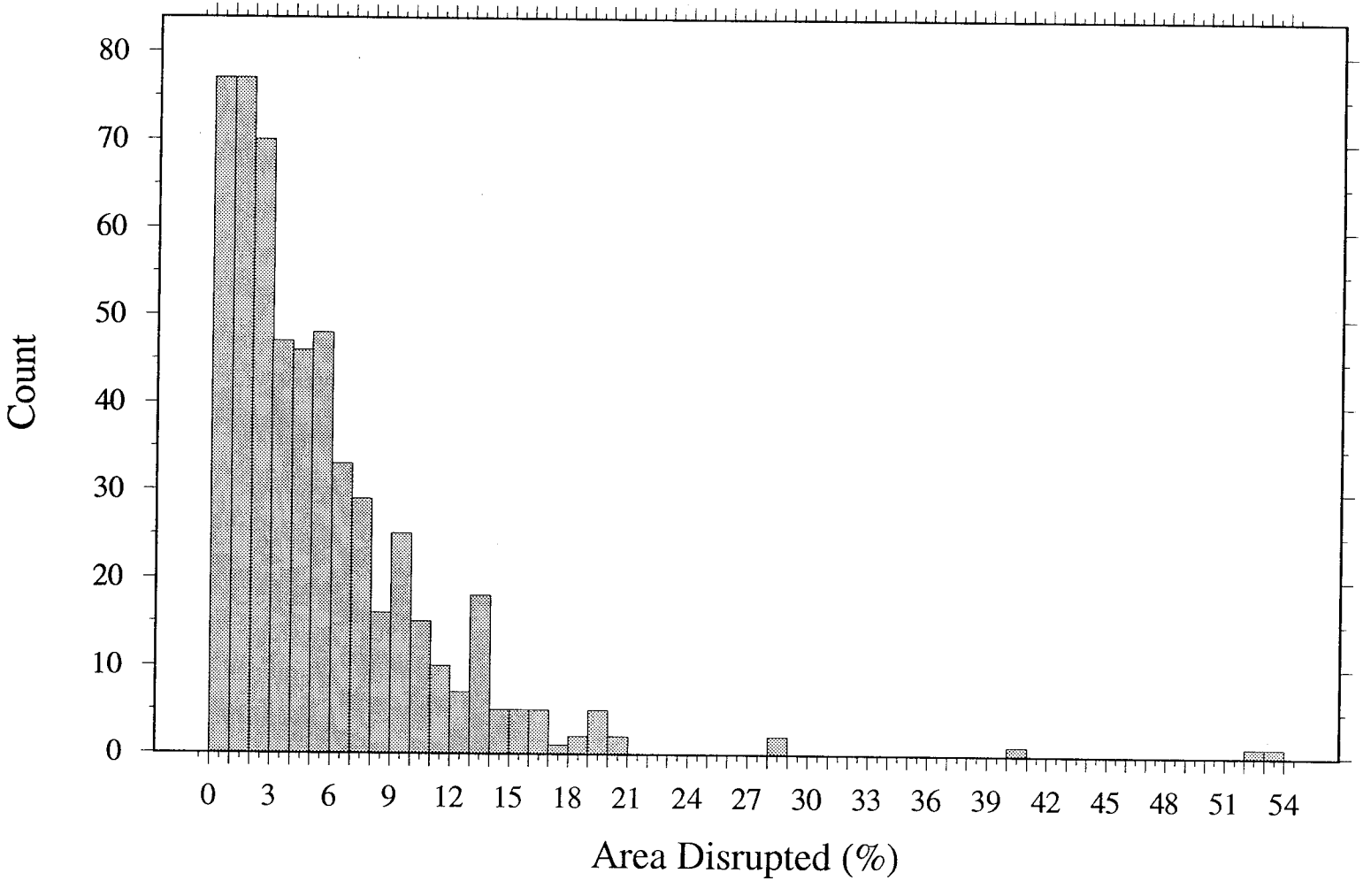
83 MTU/acre, Threshold Displacement = 0.2 m (FAULTO)

1,000,000 Realizations, Case = 2



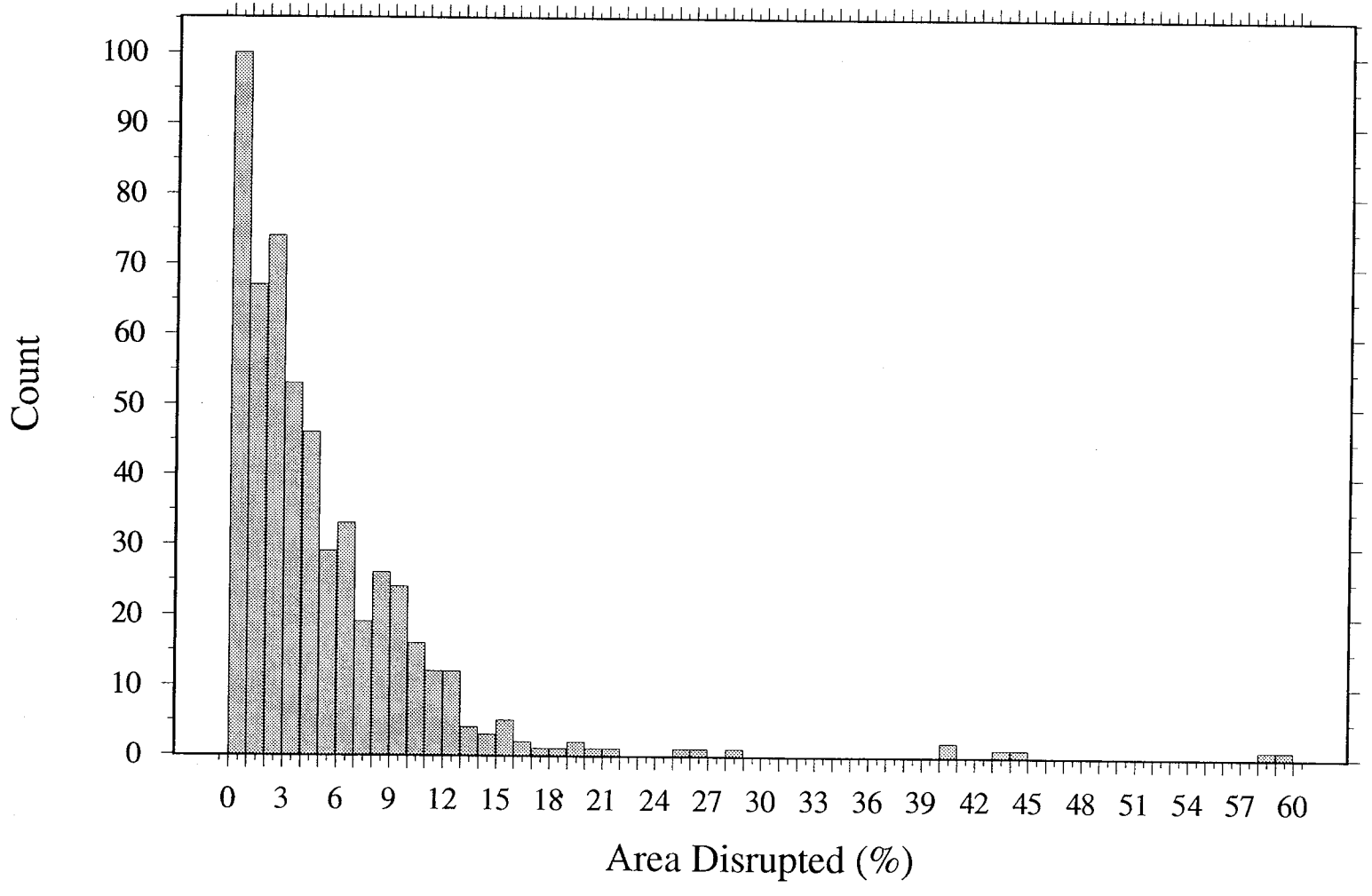
83 MTU/acre, Threshold Displacement = 0.2 m (FAULTO)

1,000,000 Realizations, Case = 3



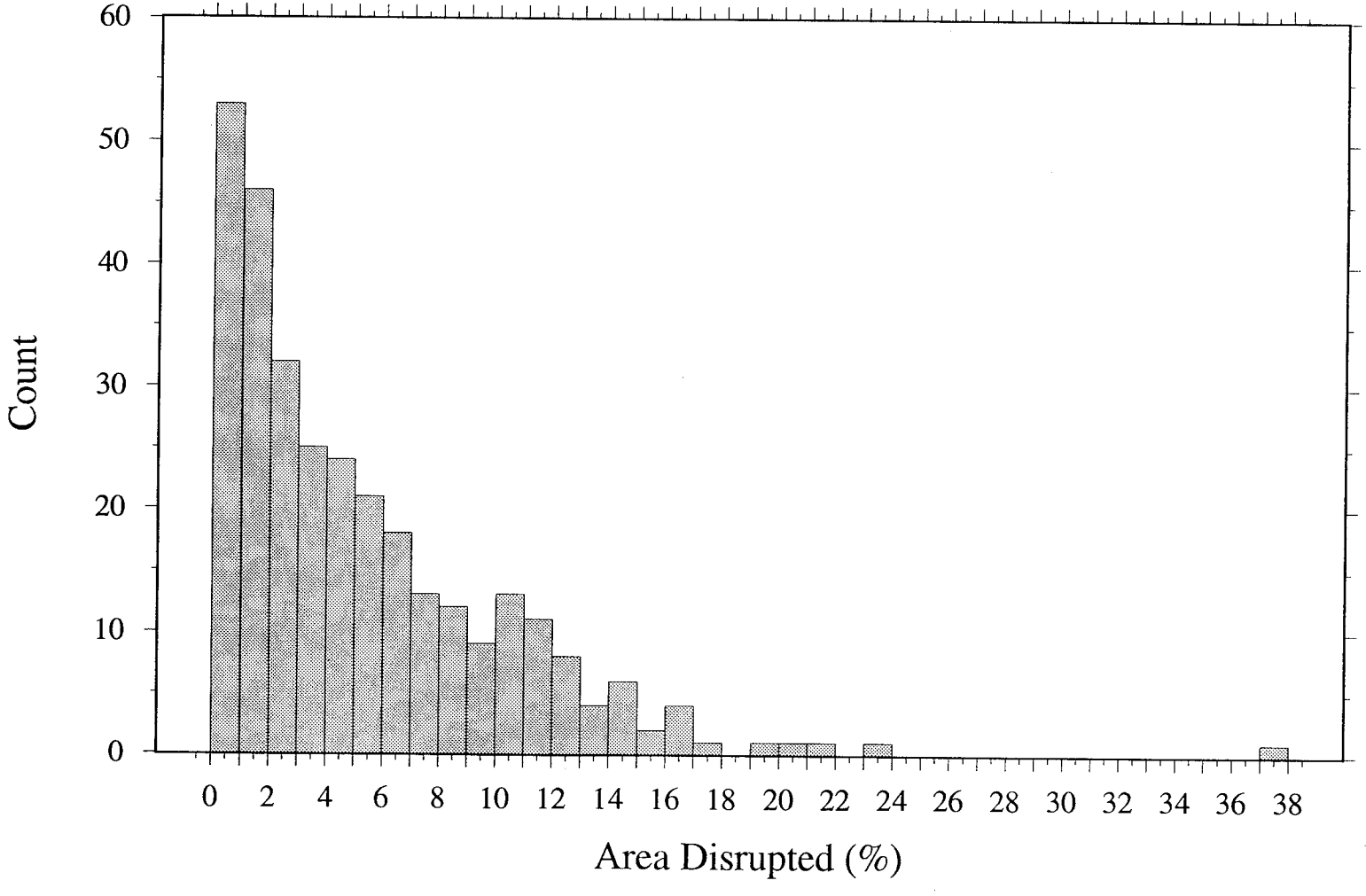
83 MTU/acre, Threshold Displacement = 0.2 m (FAULTO)

1,000,000 Realizations, Case = 4



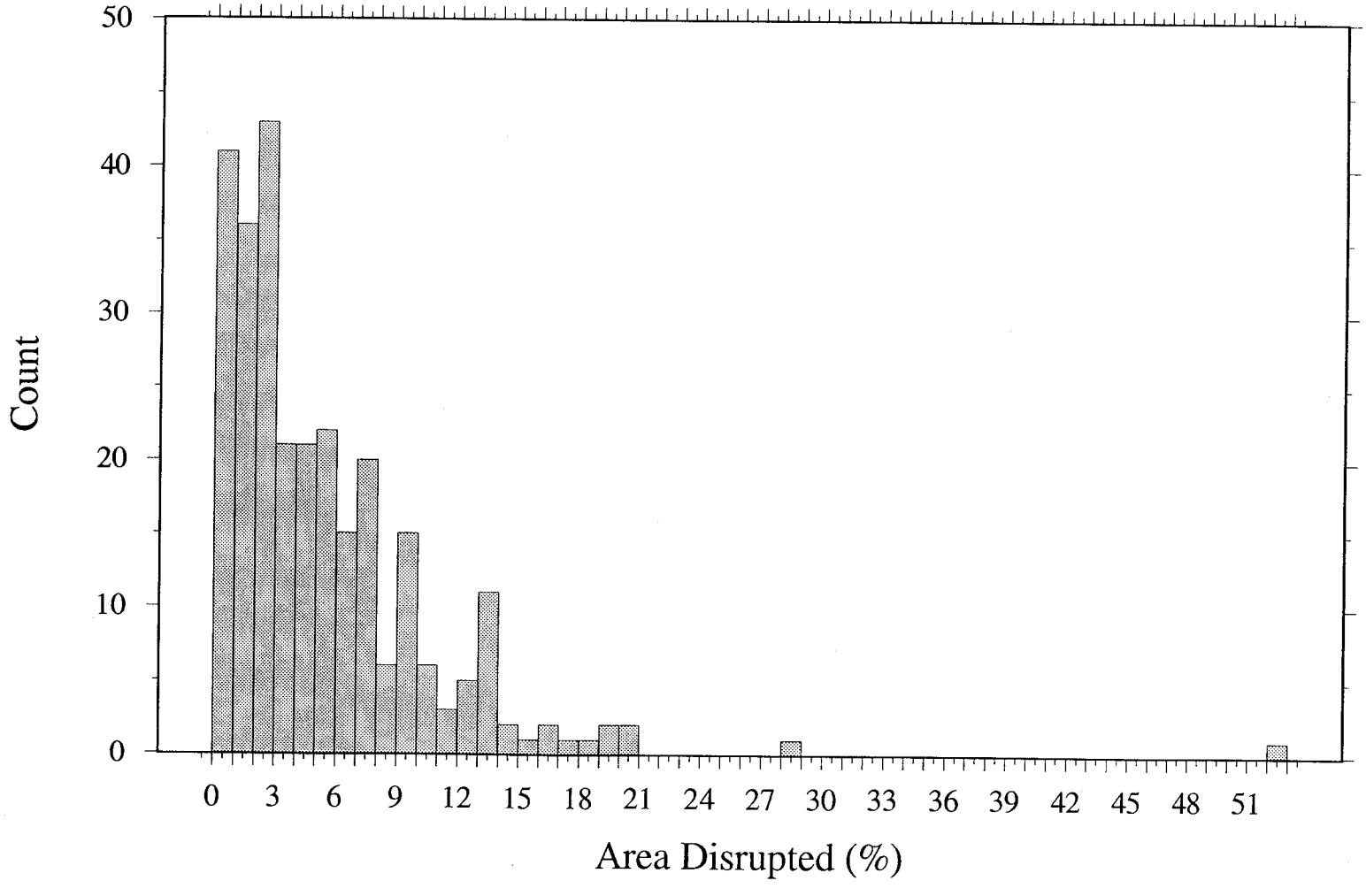
83 MTU/acre, Threshold Displacement = 0.3 m (FAULTO)

1,000,000 Realizations, Case = 1



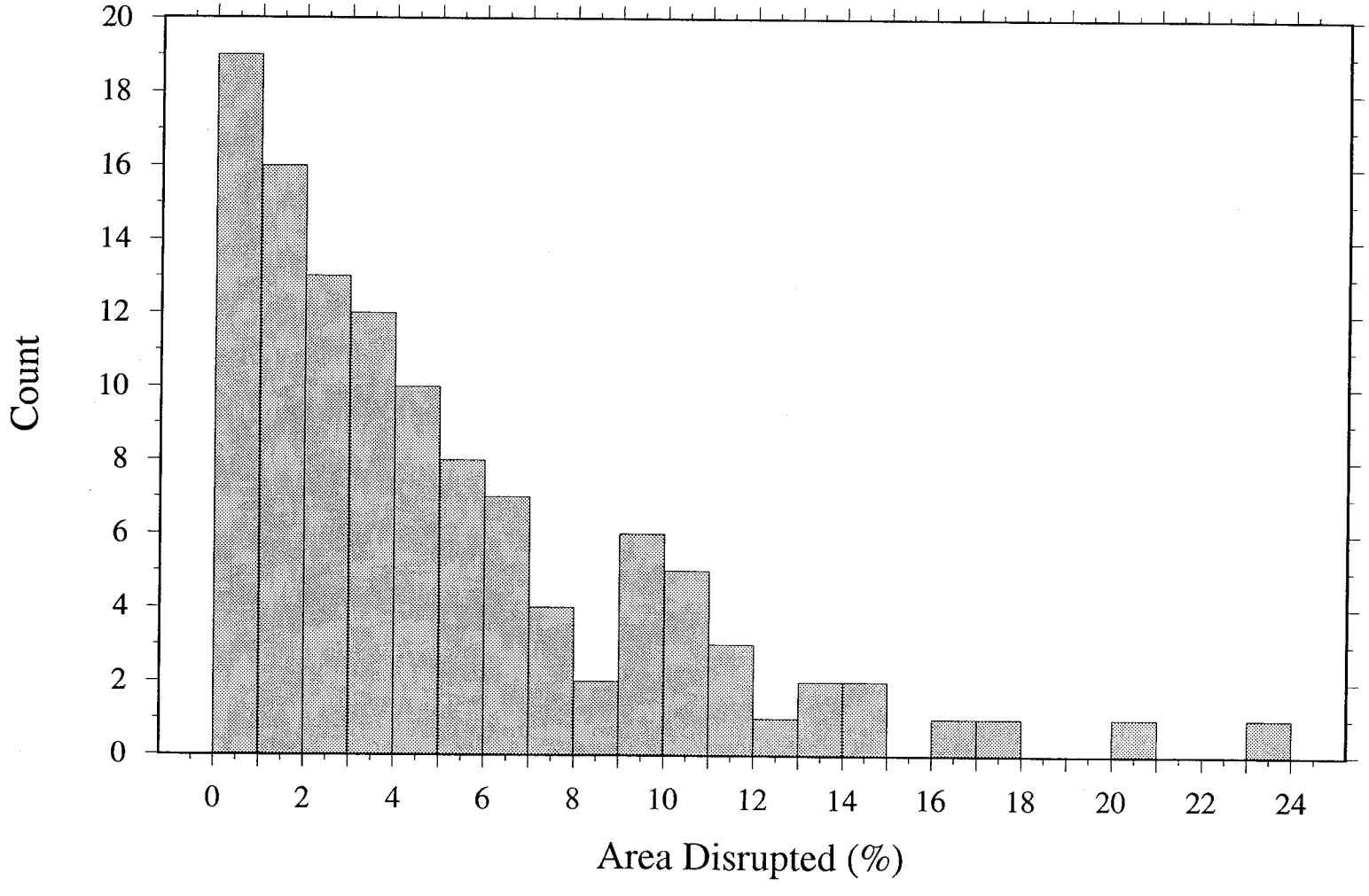
83 MTU/acre, Threshold Displacement = 0.3 m (FAULTO)

1,000,000 Realizations, Case = 2



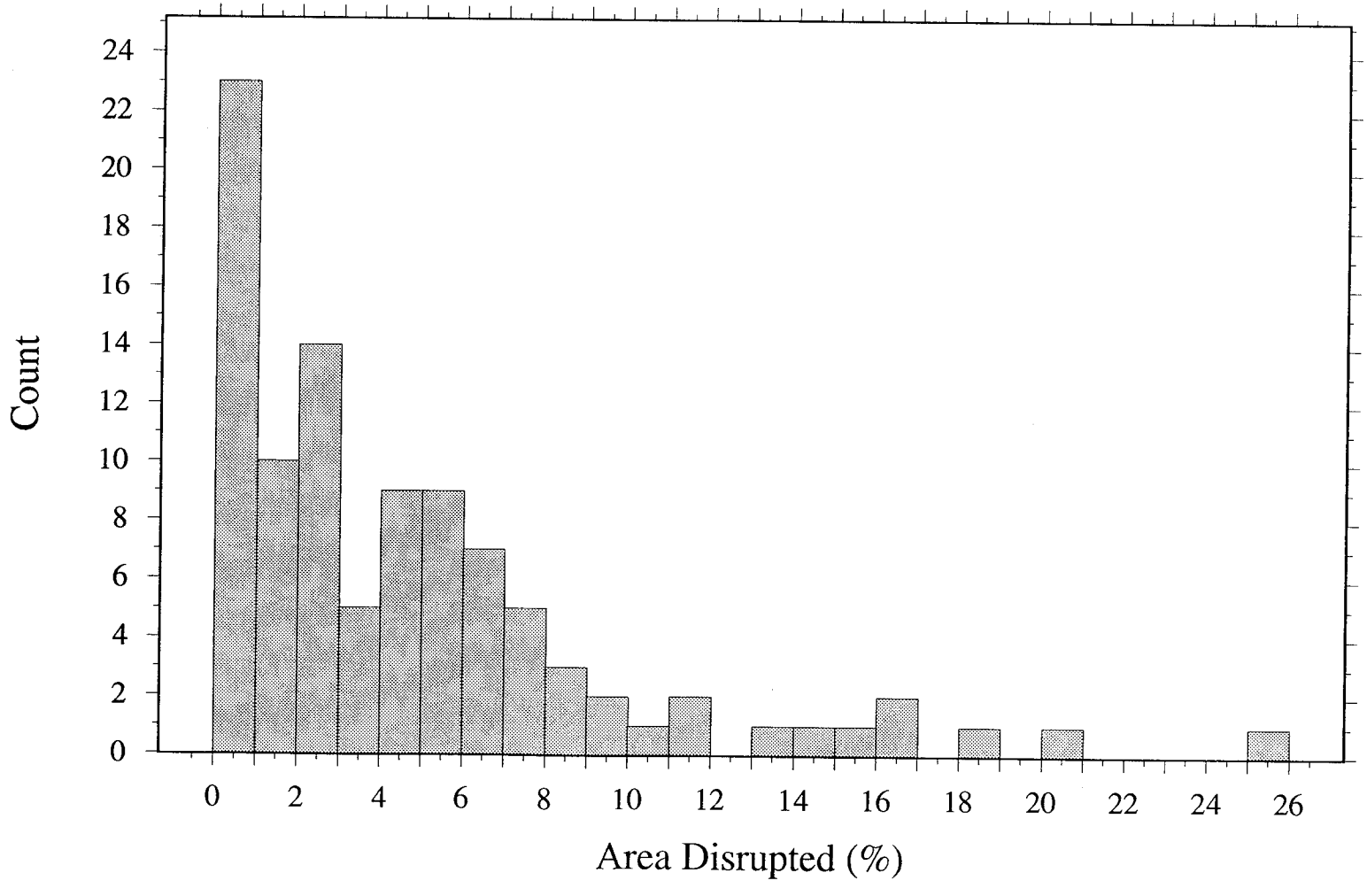
83 MTU/acre, Threshold Displacement = 0.4 m (FAULTO)

1,000,000 Realizations, Case = 1



83 MTU/acre, Threshold Displacement = 0.4 m (FAULTO)

1,000,000 Realizations, Case = 2



MEMO:

TO: B. Mabrito, QA Director

FROM: A. Ghosh and R. G. Baca

DATE: April 30, 1997

RE: FAULTING code (Version 1.0)

CC: J. Stamatakos, L. M. McKague

The FAULTING code (version 1.0) was developed to study the effects of fault displacement on waste package performance in the proposed repository at Yucca Mountain. Initially, the code was developed as a stand-alone version and a user's manual (FAULTING VERSION 1.0 – A CODE FOR SIMULATION OF DIRECT FAULT DISRUPTION TECHNICAL DESCRIPTION AND USER'S GUIDE, A. Ghosh, R. D. Manteufel, and G. L. Stirewalt, CNWRA 97-002) was issued in January 1997. Later on a simplified version of the FAULTING code was implemented in the TPA Version 3.0 as the FAULTO module. Consequently, development of the FAULTING code as an independent code is not pursued at this point. Moreover, we plan to study the effects of faulting on performance through applications of the TPA code (i.e., not through applications of the standalone FAULTING module).

CENTER FOR NUCLEAR WASTE REGULATORY ANALYSES

QA RECORDS PROCESSING WORKSHEET

Record Title:	**Development of the FAULTING Module**		
Record Date:	12/05/97		
Author:	Ghosh, A.	**Subject Code:**	308
Project Number:		**Retain Until:**	Permanent

Record Package Contents	Number of Pages
Electronic Scientific Notebook # 167	1-21
	No. of Disk(s)

VALIDATION — I attest that this record package is accurate and complete.

Element Manager: A. Laurie McKenzie	**Date:** 12/19/97
RECORDS PROCESSING	
Assigned Accession Number: Q199712150006	
Processed By: Maria Padilla	**Date:** 12.15.97

CNWRA Form QAP 16

308 ---- 0199712150006
Development fo the FAULTING
Module of Phase 3 IPA:
Sensitivity Analysis of

SCIENTIFIC NOTEBOOK
Development of the FAULTING Module

by

Amitava Ghosh

Southwest Research Institute
Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas

December 5, 1997

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1. INITIAL ENTRIES

Scientific NoteBook: # 167

Issued to: Amitava Ghosh

Issue Date: February 28, 1996

Printing Period: August 1 through November 30, 1997

Project Title: Development of the FAULTING Module of Phase 3 IPA: Sensitivity Analysis of FAULTO Module within the TPA Version 3.1.1 Code

Project Staff: Amitava Ghosh

By agreement with the CNWRA QA this NoteBook is to be printed at approximate quarterly intervals. This computerized Scientific NoteBook is intended to address the criteria of CNWRA QAP-001.

[Amitava Ghosh, February 28, 1996]

1.1. Objectives

The main task of the Structural Deformation and Seismicity (SDS) Key Technical Issue (KTI) is to analyze the probability and potential consequences of structural deformation and seismicity and related hazards to safe permanent storage of high-level nuclear waste at the candidate Yucca Mountain (YM), Nevada repository. As a part of that task, SDS KTI is evaluating the potential consequences of repository disruption from faulting. The potential consequence to faulting include rupture of waste packages (WP) directly from fault displacement. In essence, this evaluation tests Department of Energy (DOE) Waste Isolation and Containment Strategy (WICS) hypothesis regarding potential effects of structural deformation on waste package disruption. The hypothesis is

> "the amount of movement on faults through the repository horizon will be too small to bring waste to the surface, and too small and infrequent to significantly impact containment during the next few thousand years (H13)."

The present study examines the sensitivity of performance of the proposed repository to input parameters in the FAULTO module of the total system performance assessment (TSPA) code version 3.1.1. Sensitivity of input parameters to these modules is determined by their effect on the number of WPs affected and peak dose to assumed critical groups located 5 and 20 km from the proposed repository site. The FAULTO module was adapted from a stand-alone computer program called FAULTING (version 1.0) (Ghosh et al., 1997). The present analyses do not examine coupled processes, for example (i) simultaneous faulting, volcanism, and seismicity; (ii) enhanced WP degradation from seismicity or

faulting; (iii) modifications of groundwater flow in the saturated and unsaturated zones from faulting or seismicity; (iv) modifications to the near field environment from faulting and seismicity, or (v) degradation of WP strength with time due to corrosion followed by subsequent seismicity or faulting.

1.2. Computers, Computer Codes, and Data Files

Table 1-1. Computer, operating system, and compiler used in the sensitivity analysis of FAULTO module

Machine Name	Machine Type	Operating System	Compiler	Location
bigbend	SUNSPACRstation 20	SUNOS 4.1	NONE	Building 189
snowwhite	SUN SPARCstation 20	SUNOS 4.1	f77 (SUN)	Building 189

[Amitava Ghosh, November 26, 1997]

1.3. Mathematical Theory

See Ghosh et al. (1997), Stirewalt, et al. (1995), and Stirewalt, et al. (1996)

2. FAULTO MODULE

The stand-alone faulting module FAULTING and its adaptation in the TPA code (version 3.1.1) FAULTO evaluates the potential for direct waste package rupture due to fault displacement. Details about code behavior and how a faulting event is simulated are provided in Ghosh et al. (1997). Essentially the code generates a new fault randomly within the area of interest. Geometric characteristics of the fault (length, width, orientation, and displacement) as well as overall fault recurrence intervals are samples from a series of probability distribution functions (table 3.1) derived from geological observations of faults at YM (e.g., USGS, 1996).

In the original stand-alone version, the area of interest or the simulation region extends well beyond the repository footprint, thereby allowing faulting recurrence rates derived from geological observations to be used directly. For those faults that intersect the repository, the percent area affected (fault width times the fault trace length within the footprint of the proposed repository), fault displacement, and threshold displacement assumed to cause WP failure determine the number of WPs disrupted. Faulting recurrence in the stand-alone code is based on a two-tiered sampling. The recurrence rate is first sampled from a uniform distribution of recurrence rates. The sampled recurrence rate is then used to determine the

Table 2-1. Parameter values for the faulting events module of IPA phase 3

Parameter	Distribution	Value	Source
Recurrence Interval (yr)	Constant	200,000	Abstraction of regional rate from USGS (1996) paleoseismic results
Threshold displacement	discrete	0.1, 0.2, 0.3, 0.4	Assumed based on Stirewalt et al. (1995, 1996)
X location of fault	uniform	547400.0 548600.0	Within repository
Y location of fault	uniform	4076200.0 4079040.0	Within repository
Fault orientations	uniform	NW = 05% NE = 95%	ESF data (Day et. al., 1997)
Strike orientation (degrees)	normal	90% probability NW 10% NE	Day et al. (1997)
Trace Length (m)	Log normal	min = 1200 max = 50,000	DOE PSHA (unpublished)
Fault zone width (m)	beta	α =1.25 β = 15 NW (min, max) = 0.5, 275 NE (min, max) = 0.5, 365	ESF data (unpublished)
Largest credible displacement (m)	Log normal	min = 0.05 max = 1.10	DOE PSHA
Cumulative displacement rate (mm/yr)	uniform	NW min = 0.0 NW max = 5.0e-5 NE min = 0.0 NE max = 5.0e-5	EPRI (1993); Stirewalt et al. (1995); USGS (1996)

time of the faulting event based on an exponential distribution. Although this scheme is more realistic in simulating actual faulting events than the module in the TPA code (version 3.1.1), the low recurrence rate of faulting at YM requires numerous iterations in a Monte Carlo analysis (of the order of 10^5–10^6) to

obtain enough actual 'hits' to allow assessment of potential consequences in a statistically significant manner.

In the modified version of FAULTING code used in the TPA code (version 3.1.1) parameters must be sampled independently (i.e., no hierarchical or conditional sampling) prior to execution of the module. Moreover, the code runtime is too long to allow more than about 250 realizations within a reasonable time period. Therefore, in this version (FAULTO module) the recurrence interval was sampled from a single exponential distribution. As the number of realizations was low (100 realizations in all cases, except one), it is essential that the simulated faults intersects the proposed repository footprint in every realization. This is necessary to obtain statistically meaningful estimate of the consequence of faulting. As a result, the area of interest was reduced to the actual repository footprint and the recurrence interval was adjusted accordingly to yield an 'effective recurrence rate' for faulting directly in the repository.

Calculating the effective recurrence interval within the repository boundary is not straightforward because, unlike point-source events, faults are planes that have orientation and length. Moreover, both orientation and fault length have their own distributions. Recurrence rate, therefore, does not scale directly with change in simulation area. There is a critical size of the simulation region below which the recurrence interval does not increase in proportion to the reduction in simulation area. If the simulation region is smaller than the critical area, a fault could still initiate outside the area and have the necessary length and orientation to intersect the repository. To overcome this problem, an empirical solution using the stand-alone code was used. This approach is described in the following paragraphs.

The paleoseismic data recently summarized in USGS (1996) were used as a technical basis for estimating the base recurrence interval. These data indicate at least 23 earthquakes (with displacements between about 0.1 and 1.5 m) occurred in the YM Region (YMR) in the last 150,000 yr. This equates to an average recurrence interval of 6,522 yr. The paleoseismic investigations cover approximately 15 by 15 km square area. Because this recurrence interval is for all faulting (both recognized faults from which appropriate set-backs will be made for WP emplacement as well as new or under appreciated faults), we arbitrarily selected a recurrence interval for new or underappreciated faults at 13,000 yr (half the total). This value is considered conservative because most geological evidence suggests that faulting in the next 10,000 yr at YM will mostly (greater than 90 percent) occur on recognized and set-back-from faults (for example, Morris et al., 1995).

The critical size of the simulation area for faulting around the repository was developed taking into account the range of fault orientations and length of faults. In the current set of parameters (Weldy, 1997), 98 percent of the faults have lengths of 30 km or shorter or half lengths of 15 km or shorter. In addition fault orientations range between N55° W (azimuth 305°) and N25° E (azimuth 25°). Given these constraints, the size of the critical area is approximately 15.2 km × 32.8 km. The ratio of the critical area to the area used to estimate faulting recurrence from paleoseismic studies is 2.2 (498.6 divided by 225.0). Thus, the recurrence of the critical area is 5909 yr (13,000 divided by 2.2) yielding a conditional probability of 1.69×10^{-4}/yr.

This recurrence interval and the FAULTING module were used to estimate what percentage of faults generated in the critical area would actually intersect the repository. Based on a number of different realizations between 500 and 1,000,000, it appears that about three percent of the faults intersect the repository. Thus, the recurrence for faults within the repository itself is (5909 divided by 0.03) 196,967 (~200,000) yr or an annual probability (absolute probability) of 5.0×10^{-6}. This number represents a conservative estimate for faulting and is the best estimate for the base case input file.

2.1. FAULTO Parameters

The input parameters for the FAULTO module are summarized in table 3-2. Data given in this table represent a subset of the parameters in the original stand-alone version of FAULTING. In addition to the changes between the stand-alone and TPA module described in the previous section, fault dip angle, number of slip surfaces, partition of fault slip among different slip surfaces, cumulative displacement rate, and cumulative displacement rate partitioned among slip surfaces were not sampled in FAULTO. These parameters were excluded for the following reasons:

- Fault dip angle is not important because the WPs are assumed to be emplaced within a single almost horizontal horizon. Fault dips at YM are rarely less than 45°. Therefore, the problem essentially reduces to two-dimensions (2D). Variations in fault dip angle over the vertical thickness of the emplacement drifts will not affect consequence.

- Number of slip surfaces of a fault does not affect performance because the area affected is constant. The fault slip is either divided among the slip surfaces or allowed on one surface. Because the WPs are assumed to be uniformly distributed, the area affected (fault width times the trace length of the fault within the footprint of the proposed repository), not the exact location of the slip surface(s), is important.

- Cumulative displacement rates for faults at YM faults (see table 2-4 of Ghosh et al., 1997) are too small to significantly affect the performance of the proposed repository given a 10,000 yr or even 20,000 yr period of concern.

2.2. FAULTO Assumptions

There are a number of critical assumptions and simplifications inherent in the abstraction of the geological process of faulting into the numerical paradigm of the TPA code. In most cases these assumptions and simplifications are conservative, in the sense that they probably overestimate the effect on performance. In some cases, the opposite is true. The consequence may be underestimated mainly due to lack of knowledge of the exact mechanisms involved. Additionally, in some cases, the consequence of these assumptions and simplifications are not presently known and should be investigated further.

- Fifty percent of faulting is assumed to occur on new faults or faults not set back from in repository design. This assumption is very conservative because most geologists assume that,

Table 3.2. FAULTO sensitivity runs

Run	Input File	Distance to Critical Group	Time Period (yr)	Recurrence Interval (yr)	Focused Corrosion	Backfill
FLTO_Run1	Mean Value	5	20,000	200,000	no	yes
FLTO_Run2	Mean Value	5	20,000	50,000	no	yes
FLTO_Run3 (SEISMO only)	Mean Value	5	20,000	none	no	yes
FLTO_Run4	Mean Value	5	20,000	5000	no	yes
FLTO_Run5	Mean Value	5	20,000	500	no	yes
FLTO_Run6	Mean Value	20	20,000	5000	yes	yes
FLTO_Run7	Mean Value	20	20,000	200,000	yes	yes
FLTO_Run8	Mean Value	20	20,000	5000	no	yes
FLTO_Run9	Mean Value	20	20,000	500	no	yes
FLTO_Run10	Mean Value	5	20,000	5000	no	no
FLTO_Run11	Mean Value	20	20,000	5000	no	no

at YM, large faulting events will occur on known and mapped faults. For example, paleoseismic studies show that nearly all the large faults at YM produce evidence for repeated earthquake ruptures (e.g., USGS, 1996).

- There is no link between faulting, seismicity, and volcanism in the TPA (version 3.1.1) code. In nature, volcanic eruptions are always accompanied by numerous pre- and syn-eruption earthquakes (Luhr and Simkin, 1993; Fedotov and Markhinin, 1983). Likewise, all faulting events that would affect the repository would be accompanied by significant seismicity. These earthquakes would have a high frequency component and strong ground motion component because the earthquakes will be centered very close to the repository. In both cases, the assumptions are nonconservative.

- The emplacement drifts are assumed to be randomly oriented. Faults are oriented roughly north-south. If the actual emplacement drifts are subparallel to the fault trend then a much

greater number of WPs will be affected by each faulting event than currently estimated in the code. In contrast, if the emplacement drifts are mostly east-west, then the code is overestimating the effects of faulting on WP disruption.

- The TPA code limits the number of faulting events per realization to one, irrespective of the recurrence interval selected. This simplification is acceptable so long as our estimate of recurrence intervals on the order of 10^5 yr is correct and the time period of interest is 10,000 to 20,000 yr. Otherwise, this limitation reduces the potential consequence of faulting and is, therefore, nonconservative.

- There is no correlation among fault length, fault zone width, fault orientation, and probable displacement along the fault plane. This simplification is necessary as the TPA code prohibits conditionally sampling. In nature, longer faults have undergone larger displacements. Observations of fault zone widths in YMR are less constrained. Fault zone widths seem to be large for incipient faults and narrow as the fault zone matures. As the fundamental premise of this code is that faulting will occur on new faults, fault-zone widths are assumed to be wider than those observed along mature fault systems in YMR. To compensate, fault zone widths are sampled from a broad range, including the chance for a few very wide (greater than 100 m) fault zones.

- The current code does not link faulting and corrosion. In reality, corrosion over time could weaken WPs and make them more susceptible to failure by faulting. Conversely, faulting could weaken WPs and make them more susceptible to corrosion over time. In the current sensitivity studies a small threshold displacement for WP failure was used to ensure conservatism on this point.

- For WP failure from faulting, we simply assumed that once a minimum threshold displacement was exceeded, the WPs would fail. We did not link WP failure algorithm in faulting modules to a WP failure mechanism. This assumption is conservative.

- In both the stand-alone and TPA module version, all WPs intersected by the fault zone are considered failed. This conservative assumption is necessary at present because the forces WPs could encounter in fault zones are poorly understood.

- No standoff distance from the fault boundaries is assumed in the FAULTO code. Consequently, the code assumes that the damage zone due to slip along a fault will be totally restricted within the fault zone boundaries. This is a nonconservative assumption. Although it is expected that appropriate set-back distances will be kept from known and characterized faults, this will not be true for uncharacterized or new faults.

- The current code does not take into account the effects of slip on a new or an uncharacterized fault due to rupture on all existing faults in the repository region co-seismic. A new fault or

an uncharacterized fault is generated by the module without considering the faults and fractures that already exist. Any slip on the generated faults does not affect the other faults and fractures. In reality, a slip on a generated fault may have the potential to cause sympathetic slips on existing faults and fractures in YMR. As a result, number of WP disrupted by the faulting event may be significantly more than that predicted by the FAULTO module. Therefore, this assumption is clearly nonconservative.

2.3. PROCEDURES

Sensitivity analyses of different parameters of the FAULTO module in the TPA code was carried out to estimate the effects of variation of these parameters on the potential consequence of the performance of the proposed repository. A number of different combinations of disruptive scenarios (e.g., all three disruptive scenarios – faulting, seismic, and volcano – on or only faulting on) along with either focused or diffused corrosion and different recurrence intervals of the faulting events. As discussed before, location of the assumed critical group was taken either at 5 or 20 km from the proposed repository.

The repository response was measured in terms of Peak Total Equivalent Dose Estimate (Peak TEDE) (rem/year), Total EPA Release (Normalized), and number of WP disrupted. Peak TEDE for each realization was obtained from the output file *gwpkdos.res* (column 2). Column 4 of the output file *relgwgs.res* provided the Total EPA Release for each realization. Number of waste packages failed due to different disruptive events were obtained from the output file *wpsfail.res*. The sampled values of different parameters of the FAULTO module along with other sampled parameters necessary for simulation were obtained from the respective columns of the output file *samplpar.res*.

All runs of the TPA code were carried out by keeping all parameters except those in the FAULTO module and the...ground water variables at their respective mean values. Only parameters belonging to the FAULTO module were sampled from their respective population distributions. The threshold displacement level for waste package disruption was kept at 0.05 m, the minimum value of the fault slip distribution, so that any displacement along the faults would cause WP failure. In this way, systematic bias introduced by the threshold displacement on number of WP disrupted and subsequent dose calculation can be eliminated.

Additionally, complimentary cumulative distribution function plots were made for Peak TEDE values obtained in each case. The probability of exceedence of Peak TEDE values was compared with 'base case' results for different combinations of disruptive scenarios and corrosion assuming again the critical groups at 5 and 20 km from the proposed repository. In all runs, all seven subareas were used in calculations of dose.

Number of realizations for each run of the TPA code was kept usually at 100, as the runtime for 250 realizations was extremely long. As discussed before, the simulation region was taken as coinciding with the repository footprint to ensure that all simulated faults intersected the repository. Imposing this restriction on the simulation region affects the outcome of the sensitivity in some predetermined way.

Expected dependence of number of waste packages disrupted due to variation of different parameters of the FAULTO module is discussed below.

2.3.1. Effect of Fault Length

The length of the northeast trending faults ranges between 1.2 and 30 to 50 km. Therefore, number of waste packages failed will be weekly correlated with the length of faults only at the low values of fault length. At higher values of fault length, the correlation between number of waste packages failed and fault length becomes insignificant as the part of the fault within the repository boundaries will be a very small fraction of the actual fault length, as shown in figure 2-1. Consequently, the sensitivity analyses should show that the correlation between the length of faults and number of waste packages disrupted is very weak to insignificant. In reality, the correlation should be slightly stronger as faults can develop out the boundaries of the proposed repository and propagate into it.

2.3.2. Effect of Fault Orientation

The northeast trending faults have strike ranging from N5°W to N25°E. Figure 2-2 shows schematically the effects of fault orientation on number of waste package disruption. As discussed before, the orientation of the fault is linked with the estimated recurrence interval of the simulation region but the correlation is quite weak. Figure 2-2 shows that the area of the repository disrupted by fault movement does not vary significantly with the fault orientation. Therefore, it is expected that fault orientation will have negligible impact on number of waste packages disrupted and, consequently, on the doses.

2.3.3. Effect of Fault Slip and Threshold Displacement

Magnitude of fault slip should be directly correlated with the number of waste packages disrupted as the waste packages failure criterion is based on fault displacement. In all runs of the TPA code, the threshold displacement of waste packages disruption was fixed at 0.05 m, the minimum amount of fault slip. Consequently, every generated fault had a finite number of waste package disruption and magnitude of fault slip was not parameter influencing the outcome of the simulation run.

2.3.4. Cumulative Fault Displacement Rate

The cumulative fault displacement rate for the faults in the YMR is so low it is unlikely that major disruption of the proposed repository can take place within the 10,000 yr regulatory compliance period. Therefore, this factor was not taken into consideration for sensitivity analyses.

2.3.5. Fault Zone Width

The width of the simulated fault zone should be directly related with area of the proposed repository or emplacement area disrupted by the faulting event. As the waste packages are uniformly distributed over the entire emplacement area in the TPA code, the number of waste packages disrupted will be directly

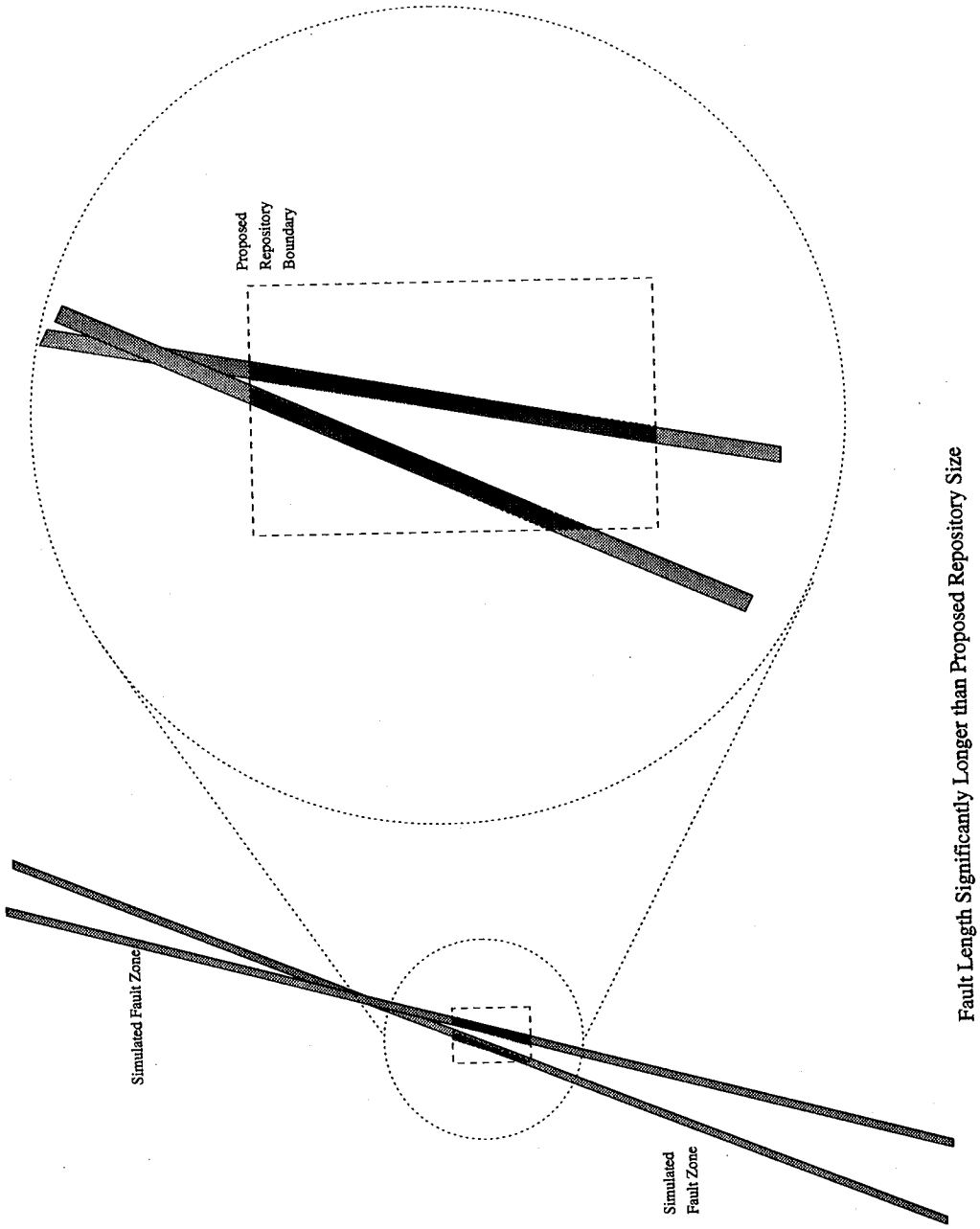

Figure 2-1a. Effect of fault zone length on waste package disruption: Fault length significantly longer than the proposed repository

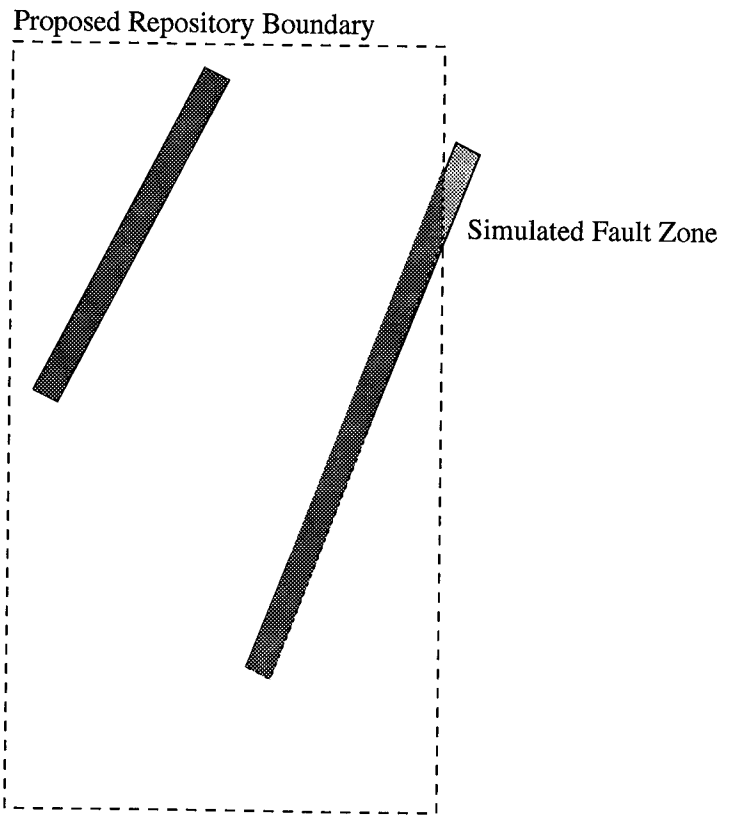

Figure 2-1b. Effect of fault zone length on waste package disruption: Fault length comparable to the proposed repository

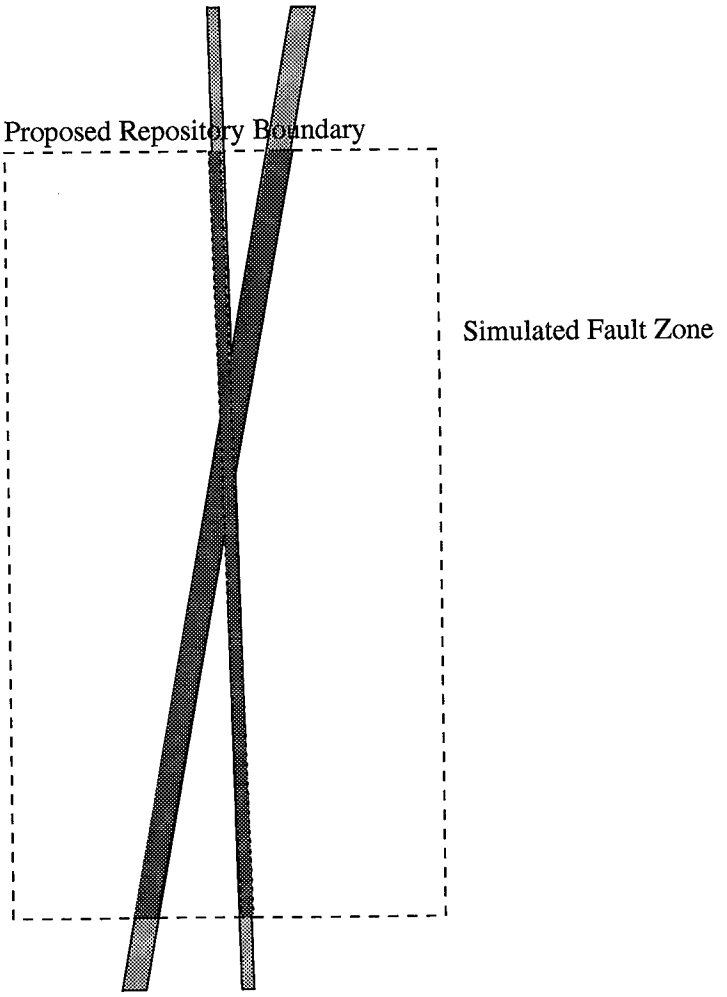

Figure 2-2. Effect of fault orientation on waste package disruption

proportional with the width of the fault zone and the correlation would be very strong, as illustrated schematically in figure 2-3.

2.4. Recurrence Interval

The recurrence interval essentially controls the time when faulting occurs. It has little impact on the number of WPs impacted because faulting is limited to one event within the period of interest. It will, however, have some influence on radionuclide transport. As the disruption of WPs takes place earlier, the radionuclides will have longer time to travel. Consequently, the probability of exceedence of a specific value of Peak TEDE experience by a focused grouped located at a given distance from the proposed repository will be higher.

2.5. Statistical Analysis

Two different approaches were adopted to estimate the correlation between each of the parameters of the FAULTO module (independent variable, **x**) with the three response variables (dependent variable, **y**):

- linear least-square regression with correlation coefficient as the measure of dependency
- nonparametric or rank correlation with Spearman rank-order correlation coefficient as the measure of dependency

Application of linear regression method to estimate dependency between **x** and **y** requires several inherent assumptions about the population distribution of x, y, and the error be true (Scheaffer and McClave, 1982). For example, both **x** and **y** should be normally distributed. The error component of the model (that is, the part of the variation observed in the dependent variable not explained by the variation of the independent variable) should also be normally distributed. Mean of this error component should be zero with constant variance for all values of the independent variable. Moreover, the errors associated with different observations of the independent variable should be independent.

One of the fundamental problems of using linear regression is that we do not necessarily know the probability distribution functions for the independent and dependent variables. In this case of the FAULTO module, several parameters are known to have probability distributions different from normal distributions. This fact can be observed in the histogram plots given in appendix A and table 2.1. For example, width of faults trending northwest has a beta distribution with $\alpha = 1.25$ and $\beta = 15$, a distribution highly skewed towards left, that is, towards small values of fault width. An alternative technique is nonparametric or rank correlation (Scheaffer and McClave, 1982; Press et al., 1986). If we replace the value of each x by the value of its rank among all x's in the sample of size N (equal to 100 in this analysis), then resulting list of numbers will be drawn from a uniform distribution between 1 and N. If some of the x's have identical values, it is conventional to assign to all these 'ties' the mean of the ranks that they would have had if their values had been slightly different. Exactly same is done for y's. If a correlation is demonstrated to be present nonparametrically, then it is really there. Nonparametric correlation is more

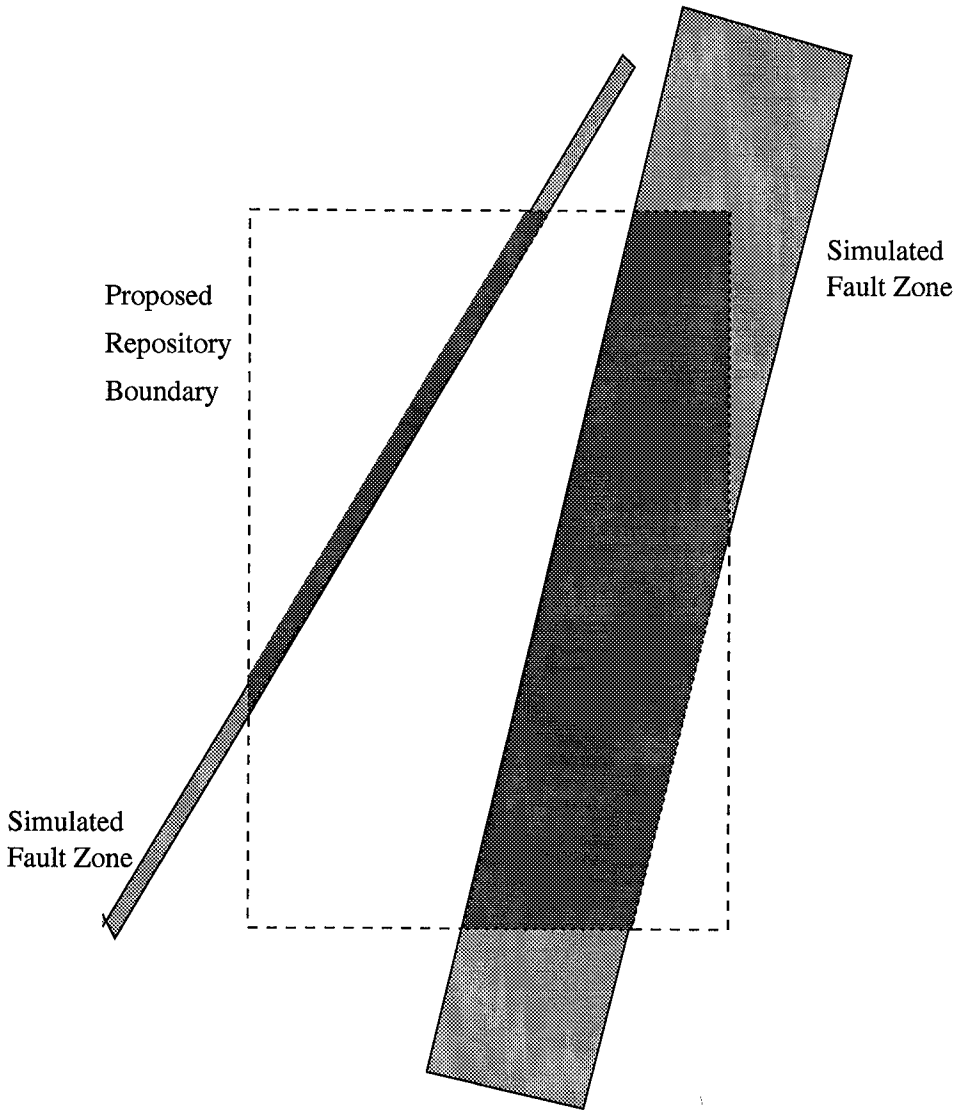

Figure 2-3. Effect of fault zone width on waste package disruption

robust than linear correlation and more resistant to outliers in the data. The methodology is given in Scheaffer and McClave (1982) and Press et al. (1986). Press et al. (1986) have provided necessary subroutines that are well-tested for calculating the Spearman Rank Correlation Coefficient. These subroutines were used in this study.

3. RESULTS AND DISCUSSION OF FAULTO SENSITIVITY ANALYSES

3.1. Sensitive Input Parameters

Results for the sensitivity runs are summarized in Appendices A-L. Results for each run are given in terms of PEAK TEDE (rem/yr), EPA release, and number of waste packages disrupted. Plots show the frequency distribution, cumulative frequency, stepwise reduction (showing the range of important parameters), correlation coefficients parameter, and the linear regressions for each input parameter tested. In all runs, the only faulting parameter that showed a significant correlation with dose of waste packages disrupted is fault zone width. Otherwise factors that control groundwater flow were the only other parameters that showed significant correlation with dose. On the basis of these results, we recommend that all parameters except fault zone width be set as constants for the total system performance investigations.

3.2. Five and 20 Kilometers

Comparison of runs in which all parameters were held constant, except for the distance to the critical group are shown in figure 3-4. Results are shown for cases in which the recurrence intervals were varied between 500 and 50,000 yr. Results show approximately 3.5 order of magnitude change in dose between 5 and 20 km. Dose of up to one rem/yr for the 5 km distance and 1.0×10^{-4} and 5×10^{-4} rem/yr for 20 km distance.

3.3. Backfilled and Unbackfilled Drifts

Comparison of runs in which the drifts were backfilled 100 yr after closure and those that assumed no backfill are shown in figure 3-5. Backfill is not assumed to affect waste package failure due to faulting, only the associated hydrological and thermal calculations. Results show that whether the drifts are backfilled or not does not influence dose response.

3.4. Focused Corrosion and Diffused Corrosion

Waste package corrosion is a critical factor in whether faulting can affect waste packages. Once the waste packages are disrupted by corrosion, they are assumed to have failed. Faulting can no longer affect repository performance. Comparison of runs in which corrosion is assured to occur and one in which focused corrosion was mitigated by changing the partial pressure of oxygen to 2.5×10^{-5} shows a nearly order of magnitude difference in dose (figure 3-6). These results show that faulting is only important to performance if focused corrosion is not a factor.

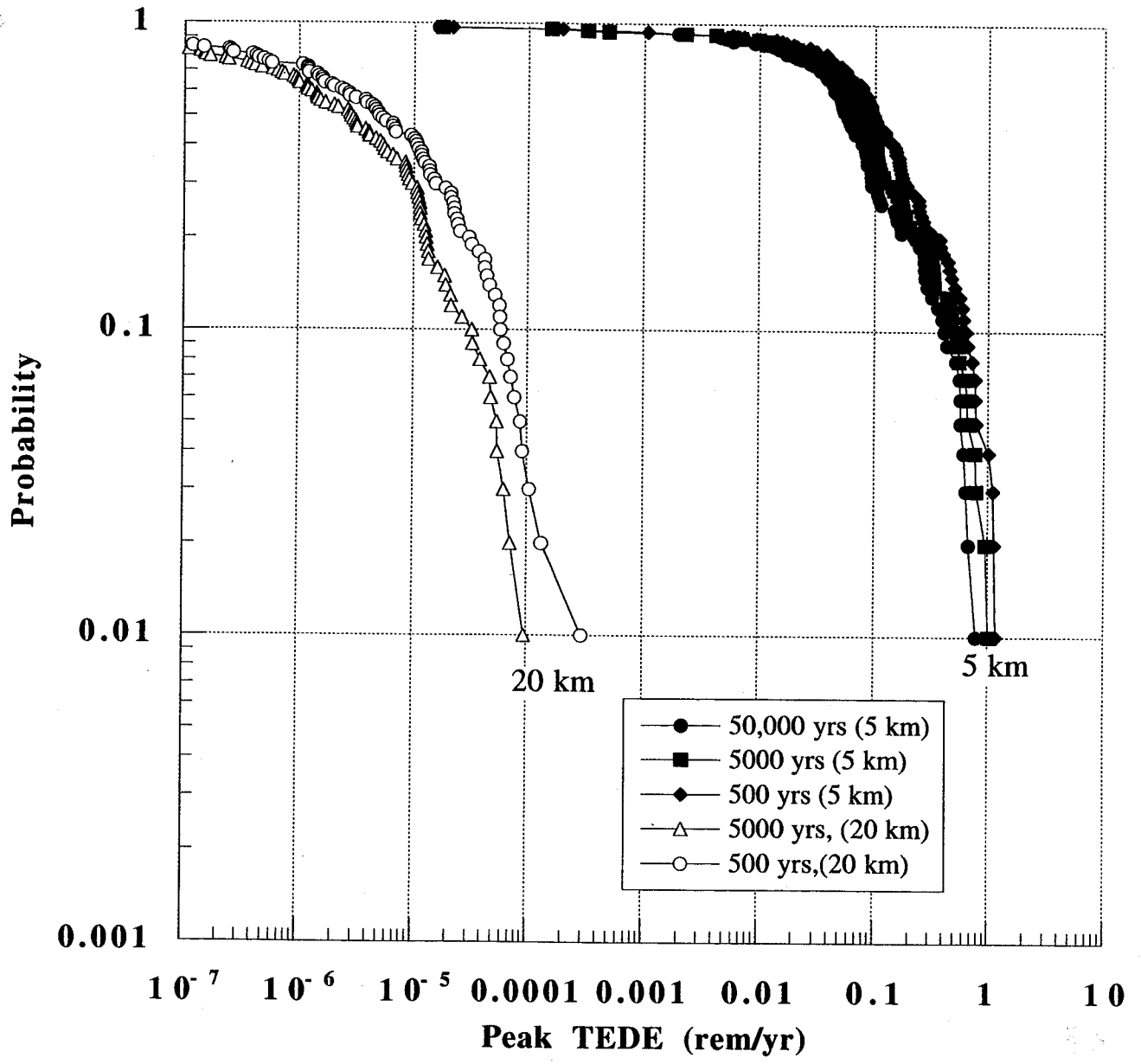

Figure 3-1. Probability plot of peak TEDE dose comparing differences in recurrence intervals for critical group at 5 and 20 km

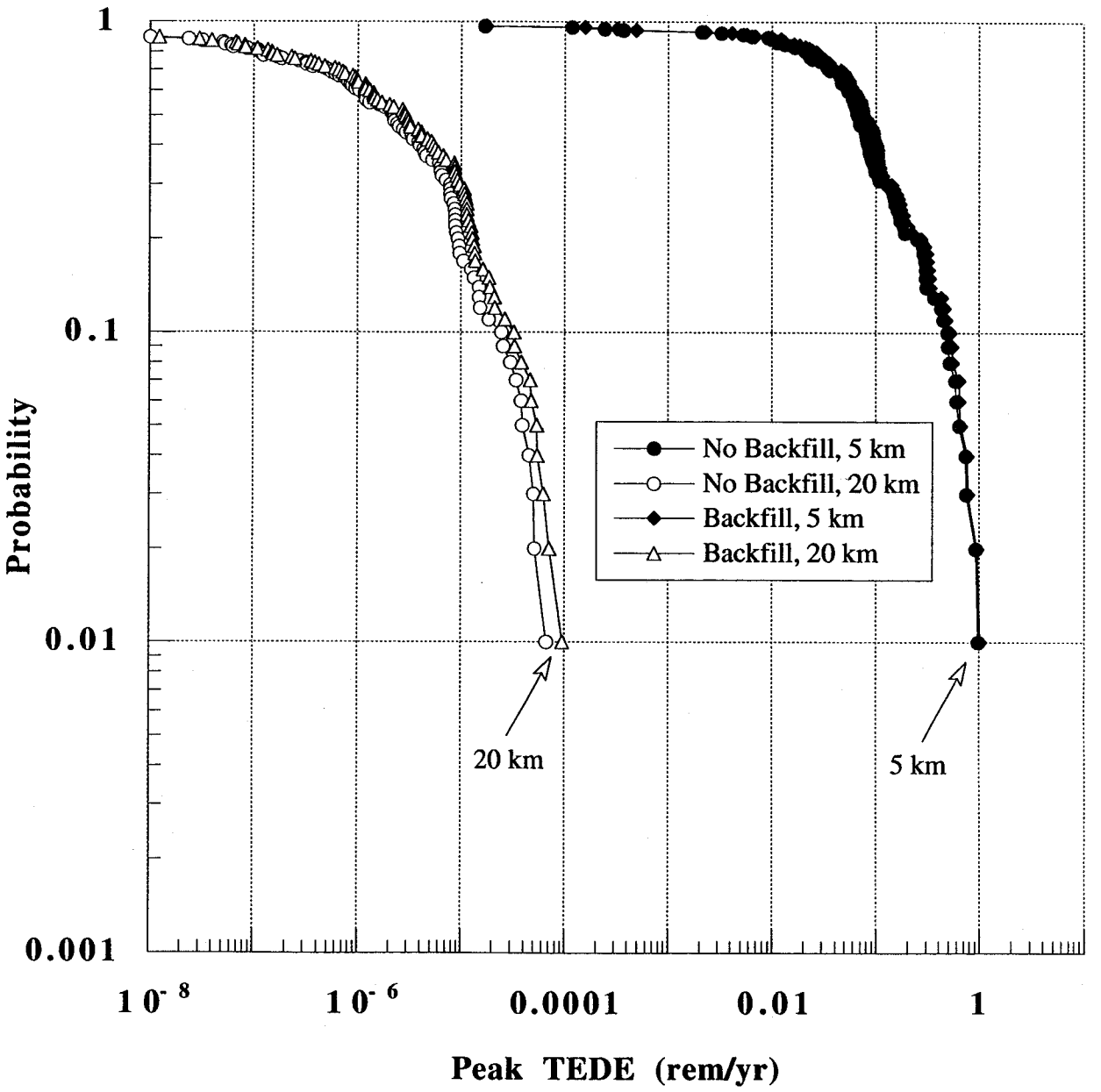

Figure 3-2. Probability plot showing differences in dose for backfilled and unbackfilled drifts for critical group at 5 and 20 km

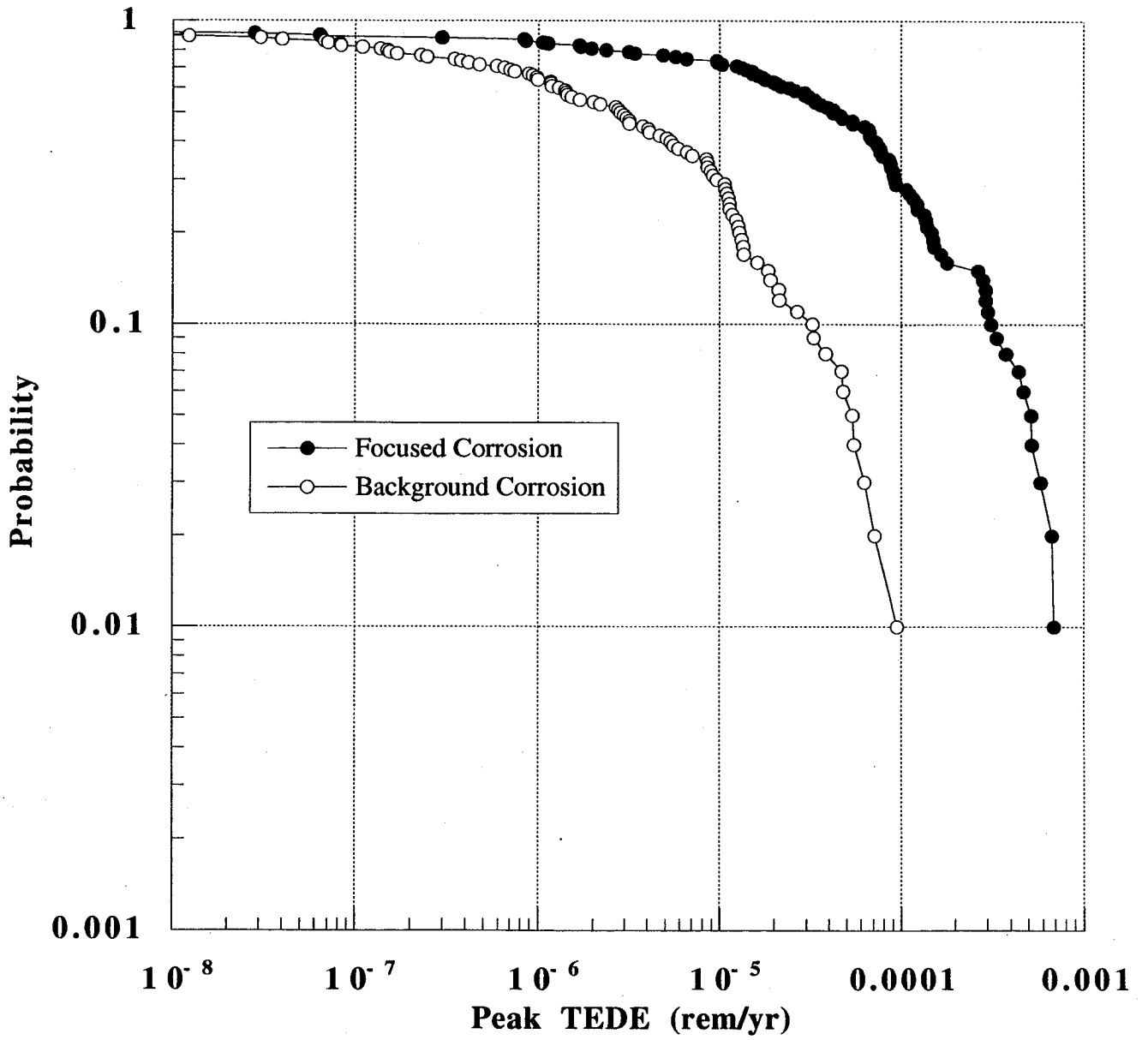

Figure 3-3. Probability plot showing difference in dose to a cultural group at 5 km for focused and background corrosion

3.5. Recurrence Rates

Changes in the recurrence rates of faulting shows marginal effects to dose (figure 3-4). Because faulting is limited to once per iteration, changes in recurrence effectively changes the time of the faulting event, not the magnitude of faulting. The increase in dose results from the increase in time available for transport to the accessible environment.

4. CONCLUSIONS AND RECOMMENDATIONS

Preliminary analyses of the FAULTO sensitivity studies reveals three conclusions and four recommendations for the total system performance analyses.

4.1. Conclusions

- Fault zone width is the most sensitive parameter in the FAULTO module
- There is mild sensitivity to the timing of the faulting event (controlled by the recurrence interval)
- Dose values from faulting are not significant compared to order-of-magnitude larger doses if focused corrosion is assumed

4.2. Recommendations

- Sample fault zone width in production TPA runs
- Hold all other faulting parameters as constants, set at the mean values
- Sample recurrence rate at 200,000 yr
- Set threshold displacement at mean value of 0.2 m

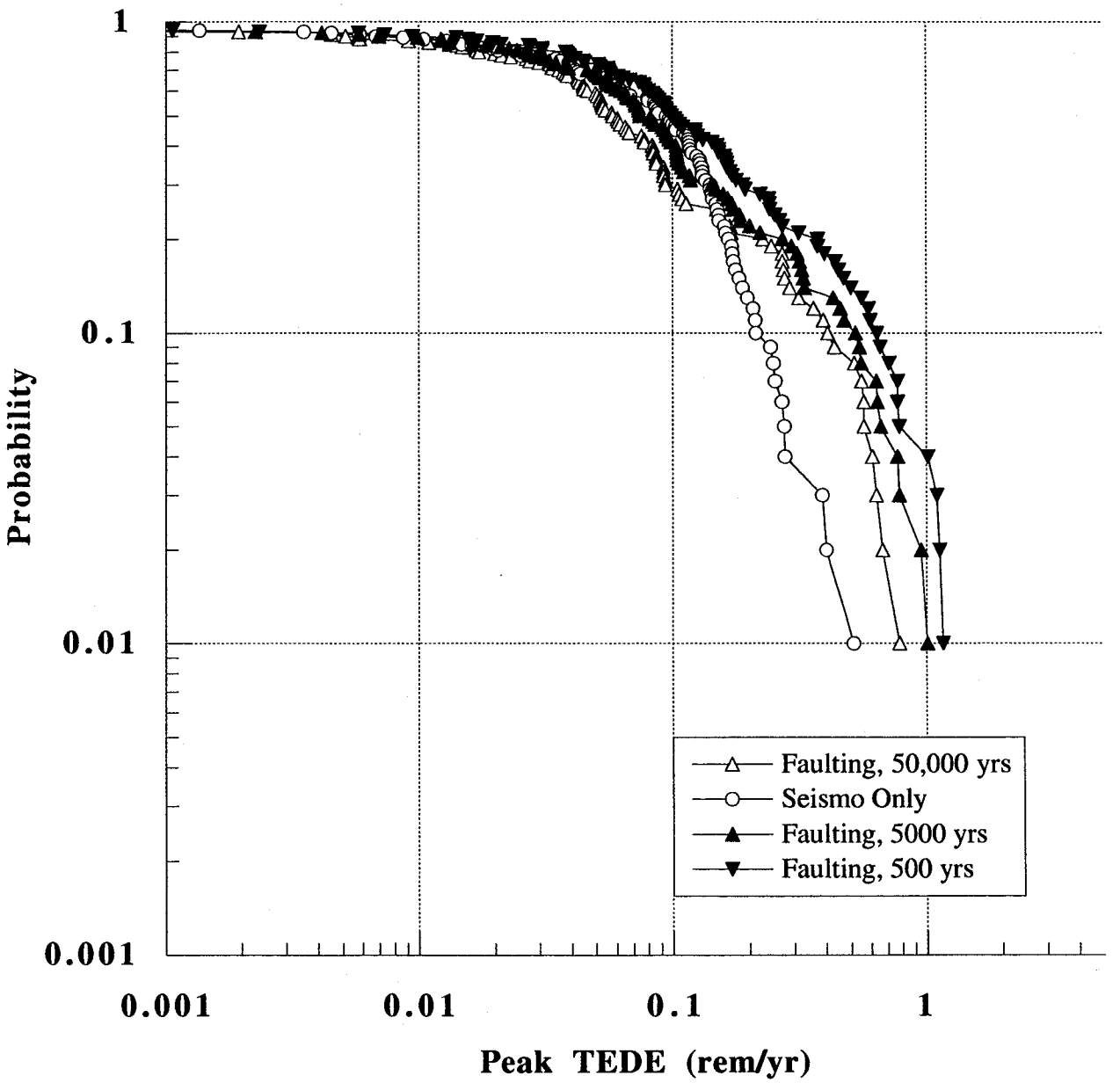

Figure 3-4. Probability plot showing dose to the critical group at 5 km for recurrence intervals between 500 and 50,000 yr

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APPENDIX A:
SENSITIVITY ANALYSES OF FAULTO MODULE

Table B-1. Correlation of FAULTO module parameters with response variables

Run	Response Variables	Time of Faulting	Threshold Displacement	NE Fault Strike	NE Fault Length	NE Fault Width	NE Fault Displacement
FLTO_Run1	Peak TEDE EPASUM No. of WP	-0.2462 -0.2918 -0.0394	NA NA NA	-0.1037 -0.0921 -0.0822	-0.0024 -0.0228 -0.0470	0.3695/0.3559 0.2175/0.2079 0.9142/0.9134	-0.0289 -0.0595 0.0523
FLTO_Run2	Peak TEDE EPASUM No. of WP	-0.1904 -0.2863 -0.0508	NA NA NA	-0.1406 -0.1673 -0.0523	0.1392 0.1692 0.0479	0.5060/0.3341 0.3527/0.2359 0.8904/0.8718	-0.0317 0.0556 -0.0860
FLTO_Run3	Peak TEDE EPASUM No. of WP	NA NA NA	NA NA NA	NA NA NA	NA NA NA	NA NA NA	NA NA NA
FLTO_Run4	Peak TEDE EPASUM No. of WP	-0.1415 -0.2043 -0.0394	NA NA NA	-0.1302 -0.1418 -0.0822	0.1306 0.1443 0.0470	0.5369/0.4119 0.4685/0.2889 0.8904/0.8718	-0.0297 -0.0070 -0.0860
FLTO_Run5	Peak TEDE EPASUM No. of WP	-0.0894 -0.0779 -0.0352	NA NA NA	-0.0953 -0.1144 -0.0822	0.1100 0.1250 0.0470	0.5532/0.4495 0.5298/0.3697 0.8904/0.8718	-0.0523 -0.0561 -0.0859
FLTO_Run6	Peak TEDE EPASUM No. of WP	0.1423 0.1142 -0.3005	NA NA NA	-0.0098 -0.0020 -0.2027	-0.0017 -0.0301 0.0355	-0.0385/0.0548 -0.0001/0.0621 0.4581/0.5434	-0.0810 -0.0831 0.0756
FLTO_Run7	Peak TEDE EPASUM No. of WP	0.0638 0.0372 -0.3354	NA NA NA	-0.0088 -0.0002 -0.1354	-0.0091 -0.0300 0.0253	-0.0562/0.0445 -0.0088/0.0573 0.4373/0.4615	-0.0790 -0.0817 -0.0715
FLTO_Run8	Peak TEDE EPASUM No. of WP	-0.1989 -0.2201 0.0020	NA NA NA	-0.0119 -0.1196 -0.2045	0.1656 -0.0165 -0.0030	0.2983/0.1733 0.3548/0.1968 0.9332/0.9494	-0.0716 -0.0682 0.0928
FLTO_Run9	Peak TEDE EPASUM No. of WP	-0.0984 -0.0905 0.0090	NA NA NA	-0.1344 -0.1258 -0.2045	0.0386 -0.0663 -0.0030	0.5078/0.2634 0.4751/0.3167 0.9332/0.9494	-0.0025 -0.0295 0.0928
FLTO_Run10	Peak TEDE EPASUM No. of WP	-0.1302 -0.1976 -0.0394	NA NA NA	-0.1299 -0.1333 -0.0822	0.1348 0.1348 0.0470	0.5345/0.4201 0.4815/0.2955 0.8904/0.8718	-0.0331 -0.0132 -0.0859

Table B-2. Correlation of FAULTO module parameters with response variables

	Response Variables	Mean Annual Infiltration	Average Precipitation	Average Temperature Increase	Flow Factor	Fmult Factor	Subarea Wet Fraction
FLTO_Run1	Peak TEDE EPASUM No. of WP	0.3143 0.3327 -0.0090	0.1505 0.0874 0.0265	-0.0385 -0.0478 -0.0190	0.1971/0.2022 0.1965/0.3163 0.0220-0.0068	0.1390/0.2338 0.1777/0.3081 -0.0425/-0.0368	0.3826/0.5296 0.3755/0.4955 -0.0044/0.0029
FLTO_Run2	Peak TEDE EPASUM No. of WP	0.3982 0.3468 0.0987	0.1496 0.0916 0.0524	-0.0739 -0.0856 -0.0565	0.1563/0.1616 0.1815/0.2810 -0.0251/0.0618	0.2583/0.1956 0.2867/0.2573 0.0228/0.0269	0.4202/0.6418 0.3422/0.5850 0.0571/0.0093
FLTO_Run3	Peak TEDE EPASUM No. of WP	0.4957 0.5575 NA	0.2074 0.0172 NA	-0.2043 -0.0979 NA	0.1684/0.1406 0.2200/0.3260 NA	0.3122/0.2238 0.3714/0.2841 NA	0.6072/0.7406 0.52540.6153 NA
FLTO_Run4	Peak TEDE EPASUM No. of WP	0.4172 0.4251 0.0987	0.1238 0.0616 0.0524	-0.0758 -0.0521 -0.0565	0.1165/0.1224 0.1568/0.2815 -0.0251/0.0618	0.2841/0.1876 0.2914/0.2503 0.0228/0.0269	0.4453/0.6362 0.4079/0.5737 0.0571/0.0093
FLTO_Run5	Peak TEDE EPASUM No. of WP	0.4363 0.4657 0.0987	0.1102 0.0194 0.0524	-0.0772 -0.0293 0.0565	0.1217/0.0902 0.1350/0.2777 -0.0251/0.0618	0.2474/0.1483 0.2615/0.2328 0.0228/0.0269	0.4763/0.6409 0.4520/0.5618 0.0571/0.0093
FLTO_Run6	Peak TEDE EPASUM No. of WP	0.4381 0.4978 -0.0303	-0.0810 -0.0586 -0.0963	-0.0579 -0.0975 0.1078	0.3173/0.5053 0.2697/0.4733 0.1520/0.0682	0.2869/0.3864 0.3035/0.3853 0.0307/0.0772	0.3611/0.3693 0.4394/0.3802 -0.1011/0.0182
FLTO_Run7	Peak TEDE EPASUM No. of WP	0.4335 0.4957 0.0518	-0.0798 -0.0583 0.0712	-0.0611 -0.0970 -0.0064	0.3231/0.5033 0.2737/0.4767 -0.0617/0.0121	0.2872/0.3908 0.3039/0.3853 0.0202/-0.0079	0.3558/0.3691 0.4370/0.3776 0.0620/0.0517
FLTO_Run8	Peak TEDE EPASUM No. of WP	0.3659 0.4296 0.0893	-0.0731 -0.0921 -0.0351	0.0209 -0.0426 0.0318	0.0935/0.4449 0.0721/0.4348 -0.1076/-0.0103	0.1480/0.3666 0.1465/0.3495 -0.0174/0.0367	0.3230/0.3710 0.3915/0.3657 0.0581/0.0176
FLTO_Run9	Peak TEDE EPASUM No. of WP	0.3293 0.4121 0.0893	-0.1087 -0.1238 -0.0351	0.0416 -0.0366 0.0318	0.0547/0.4323 0.0708/0.4034 -0.1076/-0.0103	0.1137/0.3643 0.1870/0.3655 -0.0174/0.0367	0.2891/0.3643 0.3666/0.3637 0.0581/0.0176
FLTO_Run10	Peak TEDE EPASUM No. of WP	0.4159 0.4369 0.0987	0.1192 0.0596 0.0524	-0.0697 -0.0455 0.0565	0.0127/0.0249 0.0177/-0.0125 0.0007/0.0861	0.0223/0.0467 0.0106/0.0415 0.0077/0.0018	-0.1223/0.1379 0.1510/0.2890 -0.0251/0.0618

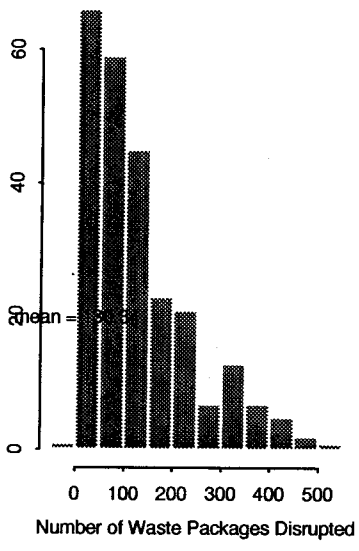
APPENDIX B:

Run: FLTO_Run1

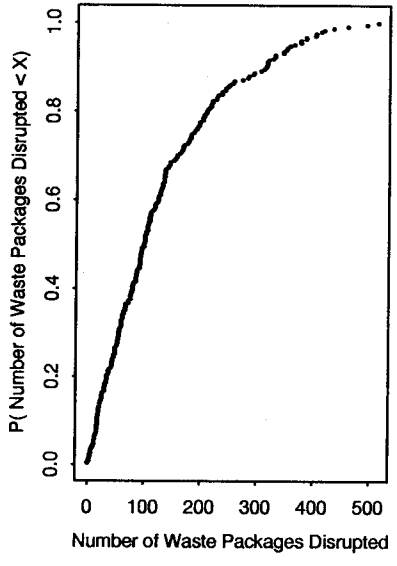
Distance to Focused Group = 5 km
Recurrence Interval = 200,000 years
Only FAULTO with Diffused Corrosion
With Backfill

5 km Scenario
Summary Plots for Number of Waste Packages Disrupted

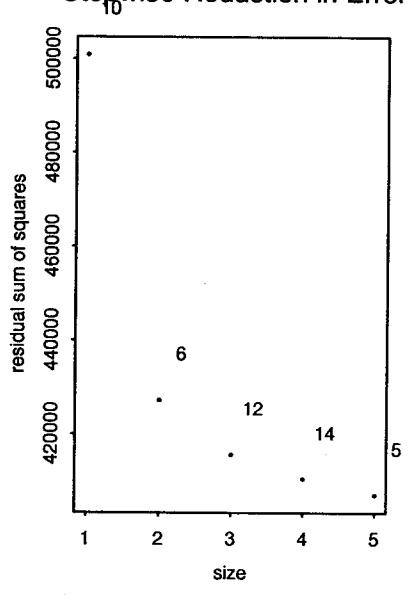
Frequency Distribution



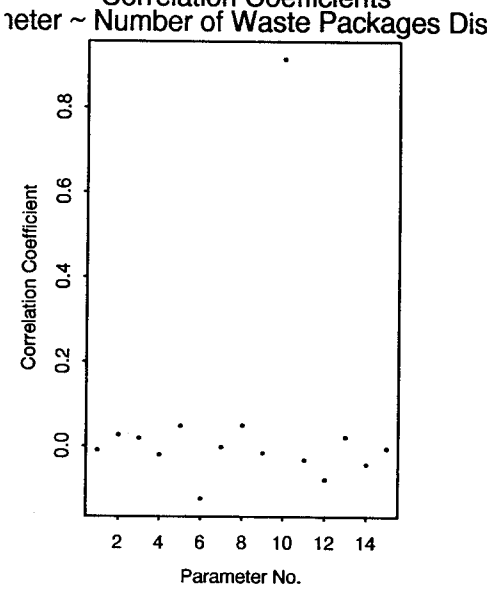
Cumulative Frequency



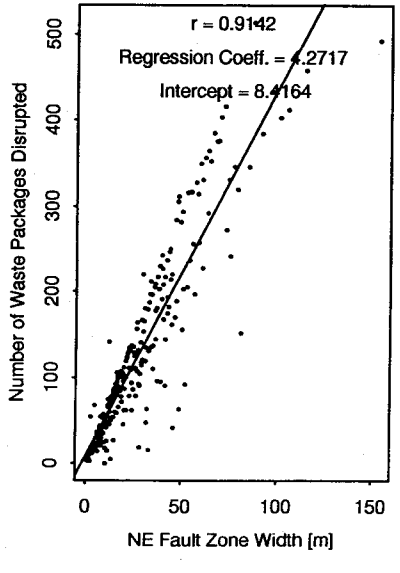
Stepwise Reduction in Error



Correlation Coefficients



Parameter No. 10



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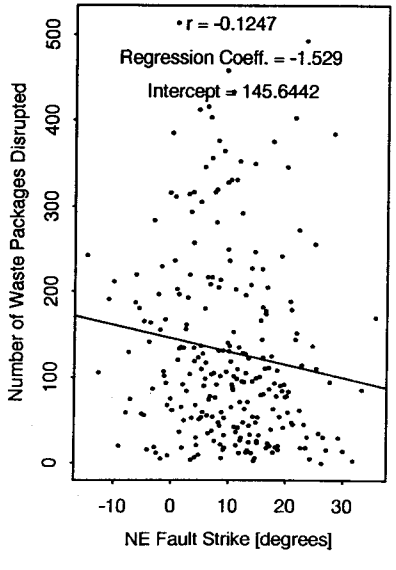
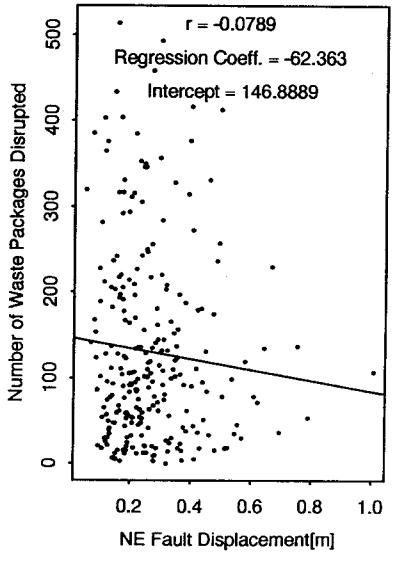
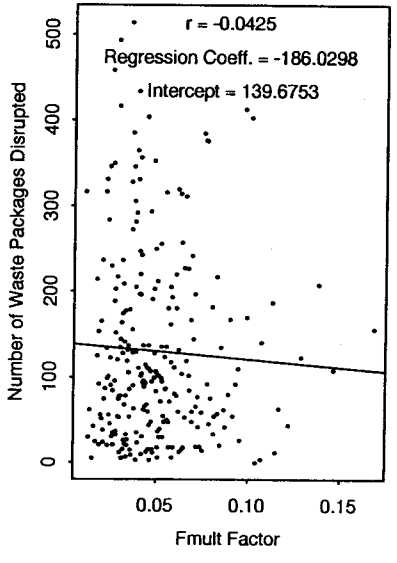


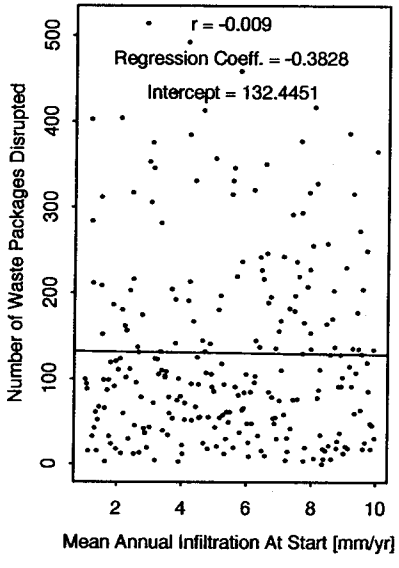
Parameter No. 12



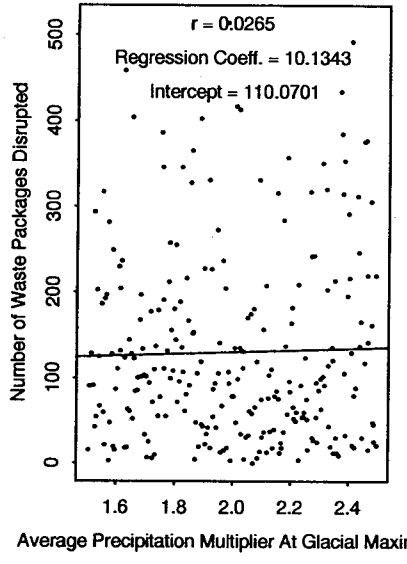
Parameter No. 14



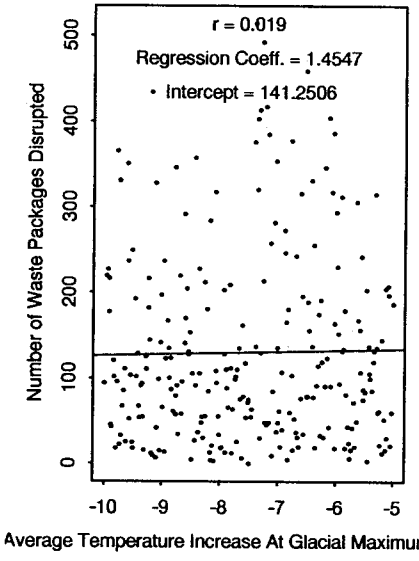
Parameter No. 1



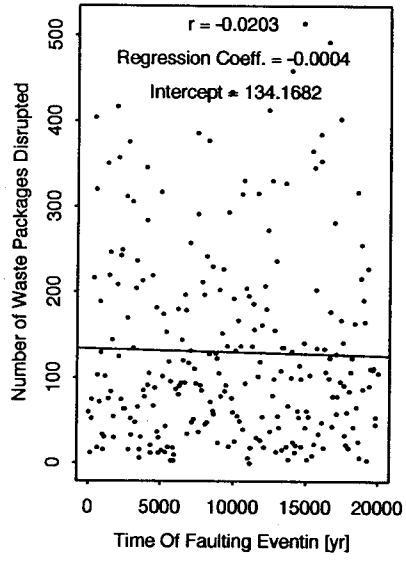
Parameter No. 2



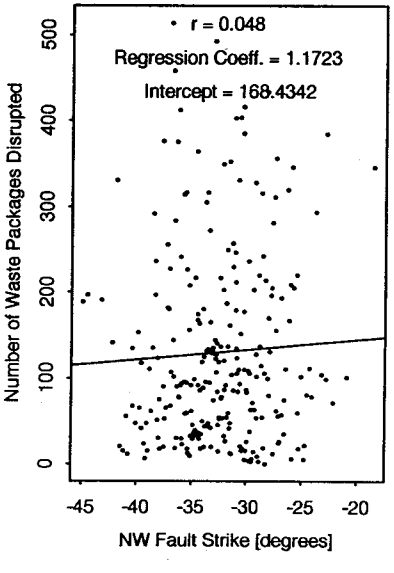
Parameter No. 3



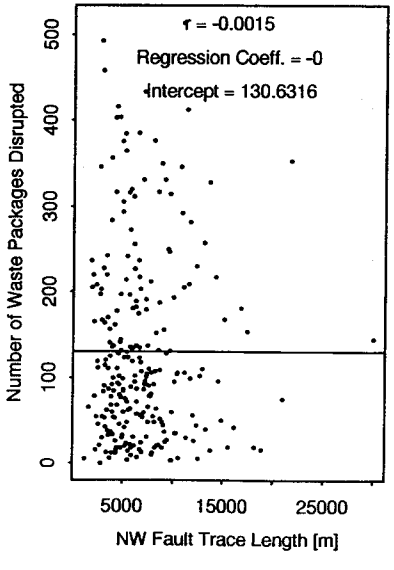
Parameter No. 4



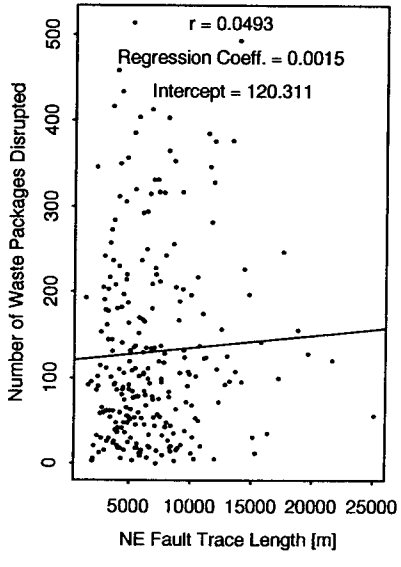
Parameter No. 5



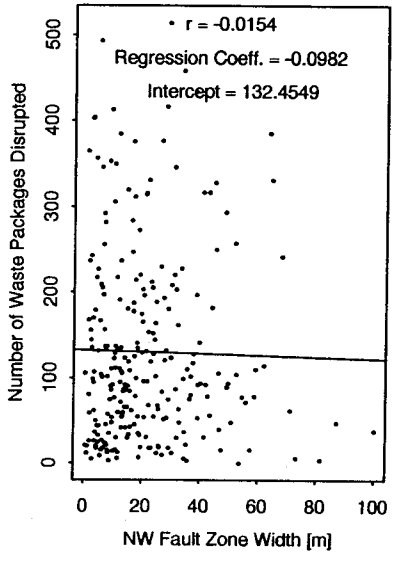
Parameter No. 7

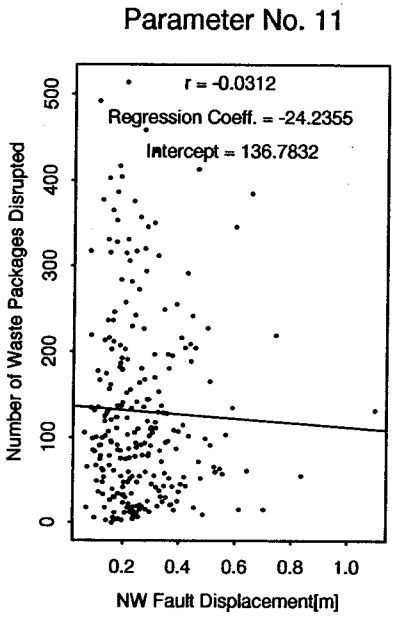


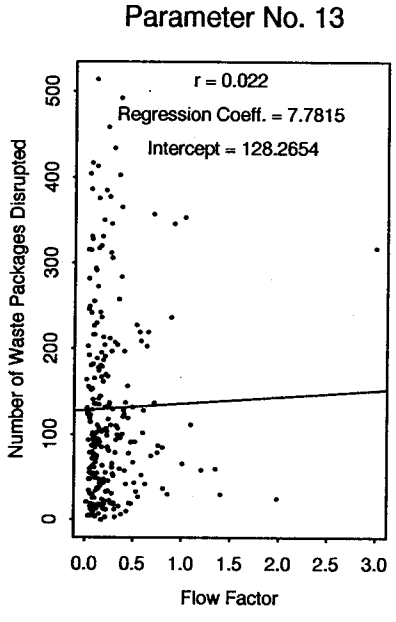
Parameter No. 8

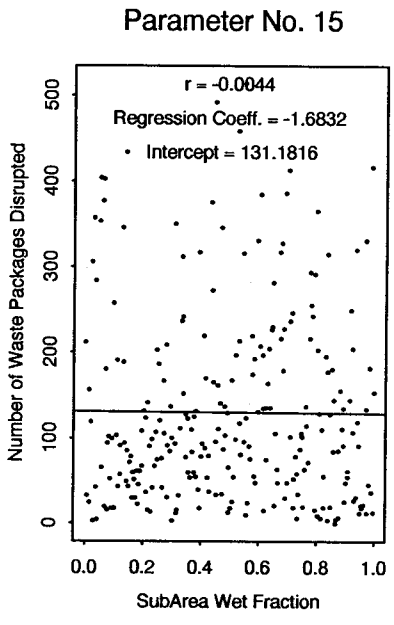


Parameter No. 9



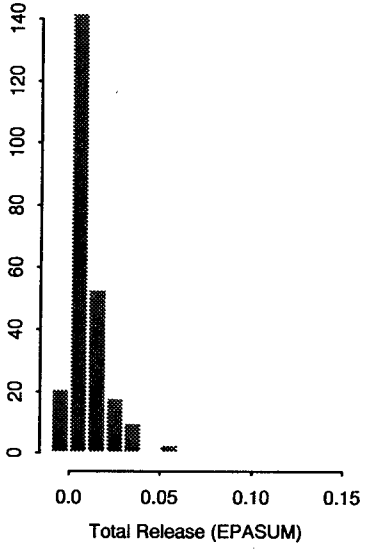

Parameter No. 11
r = -0.0312
Regression Coeff. = -24.2355
Intercept = 136.7832
Number of Waste Packages Disrupted
0
100
200
300
400
500
0.2
0.4
0.6
0.8
1.0
NW Fault Displacement[m]


Parameter No. 13
r = 0.022
Regression Coeff. = 7.7815
Intercept = 128.2654
Number of Waste Packages Disrupted
0
100
200
300
400
500
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Flow Factor

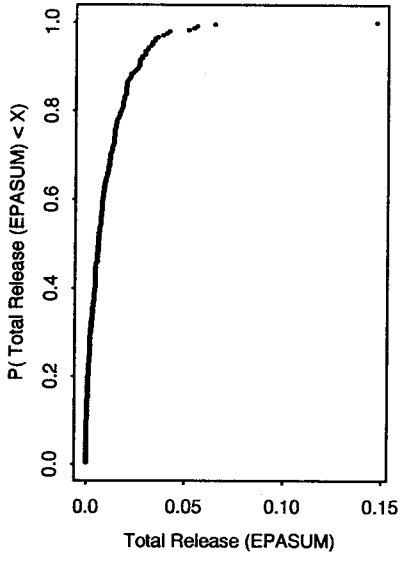

Parameter No. 15
r = -0.0044
Regression Coeff. = -1.6832
Intercept = 131.1816
Number of Waste Packages Disrupted
0
100
200
300
400
500
0.0
0.2
0.4
0.6
0.8
1.0
SubArea Wet Fraction

5 km Scenario
Summary Plots for Total Release (EPASUM)

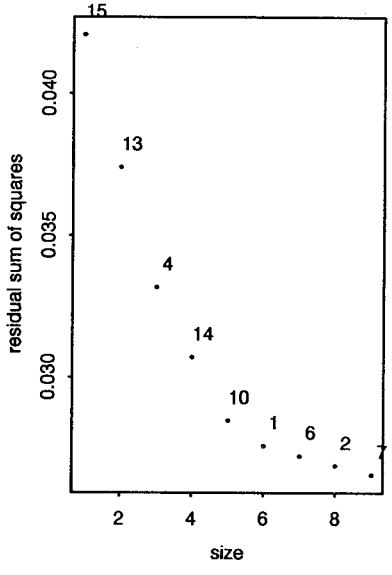
Frequency Distribution



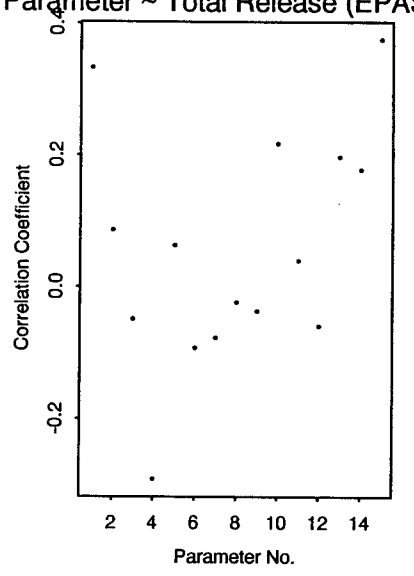
Cumulative Frequency



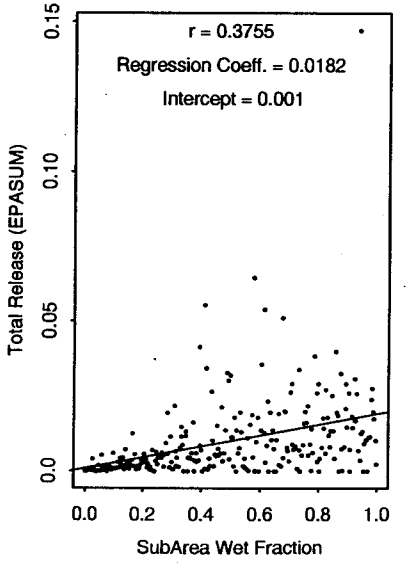
Stepwise Reduction in Error



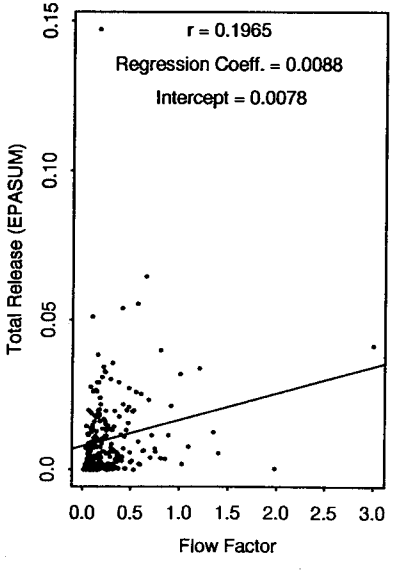
Correlation Coefficients
Parameter ~ Total Release (EPASUM)



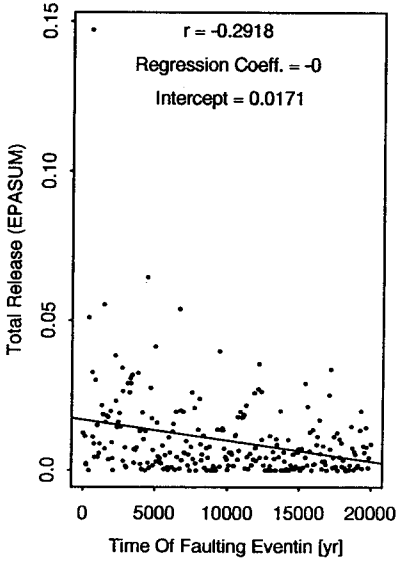
Parameter No. 15



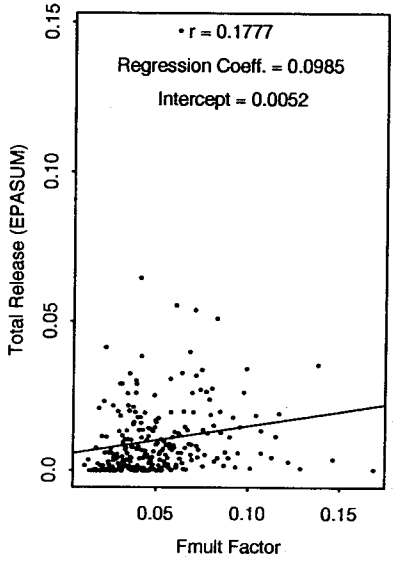
Parameter No. 13



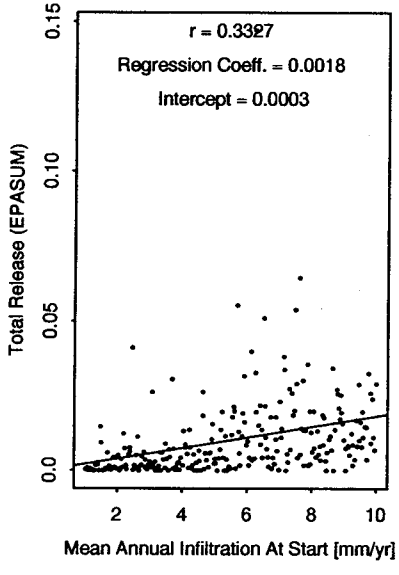
Parameter No. 4



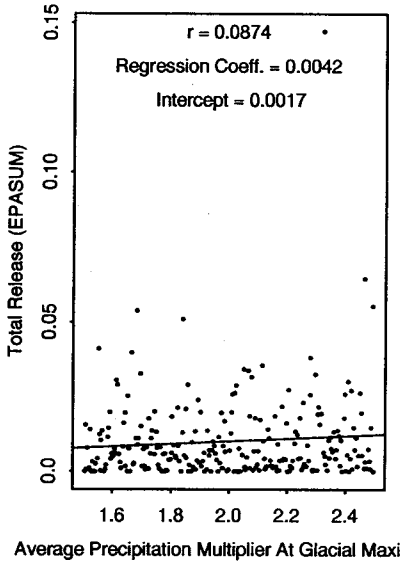
Parameter No. 14



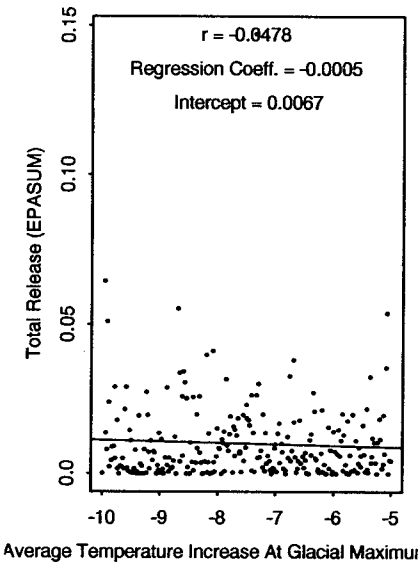
Parameter No. 1



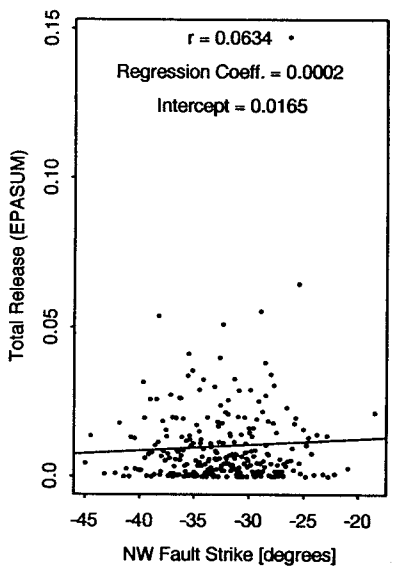
Parameter No. 2



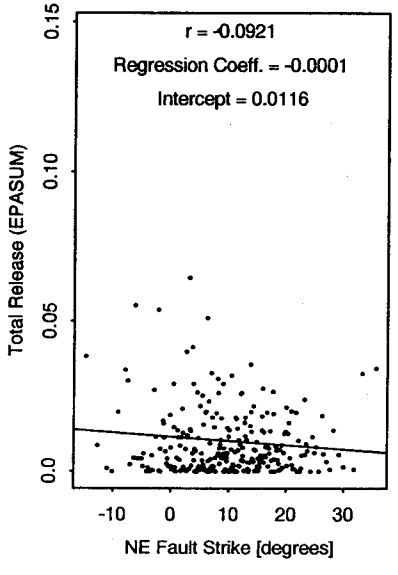
Parameter No. 3



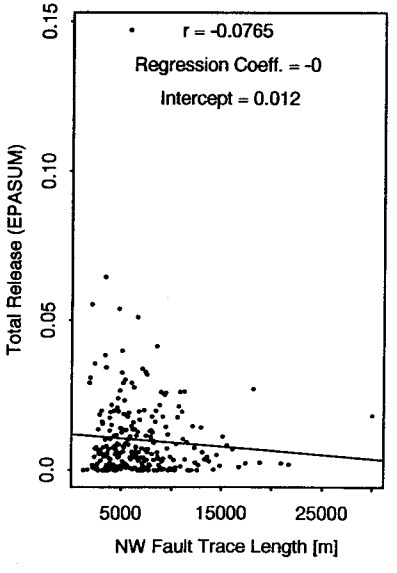
Parameter No. 5



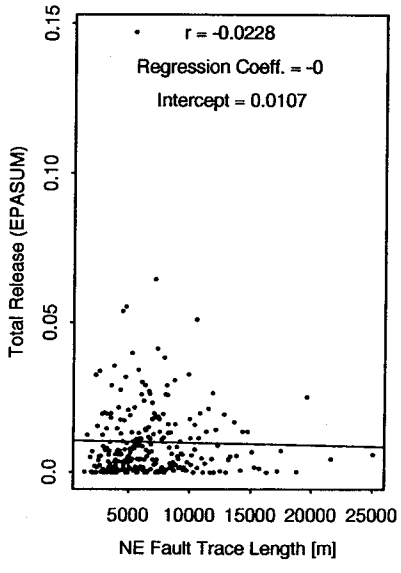
Parameter No. 6



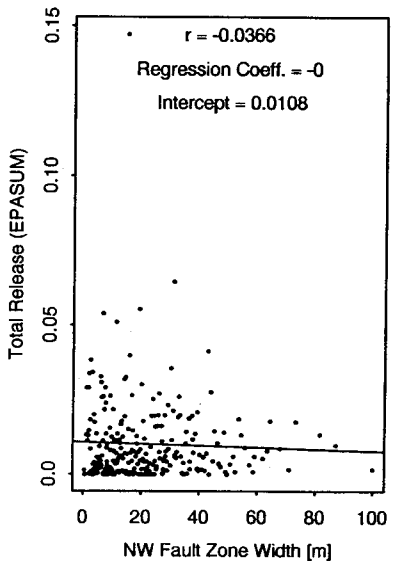
Parameter No. 7

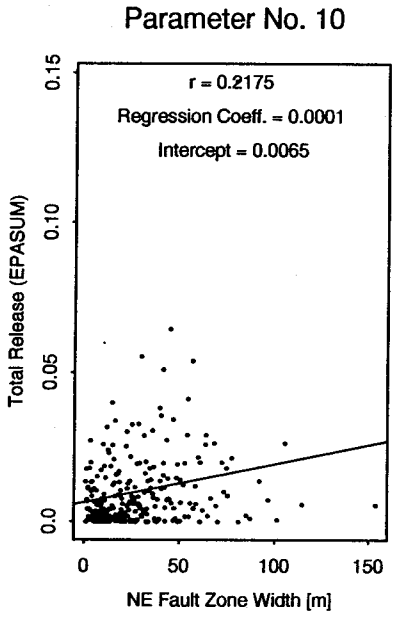


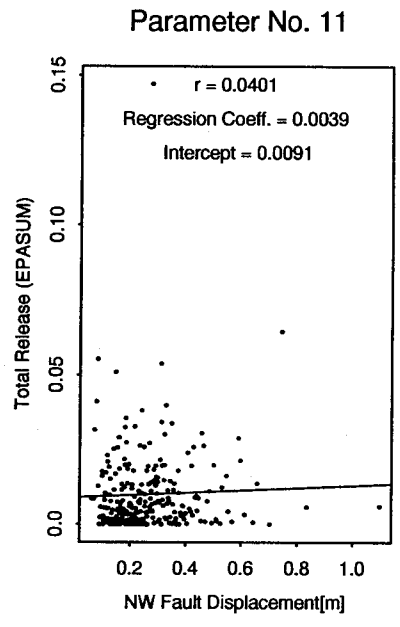
Parameter No. 8

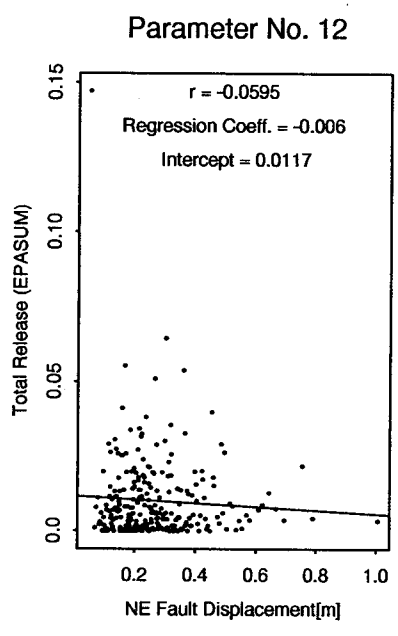


Parameter No. 9



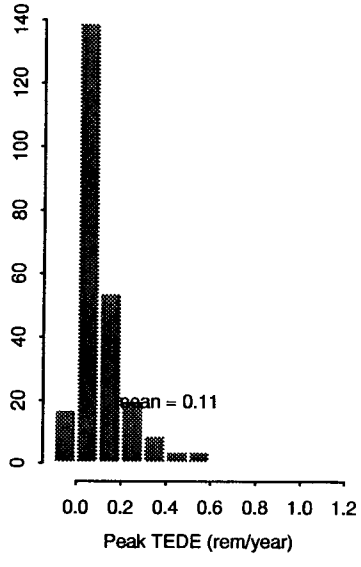

Parameter No. 10
r = 0.2175
Regression Coeff. = 0.0001
Intercept = 0.0065
Total Release (EPASUM)
0.0
0.05
0.10
0.15
0
50
100
150
NE Fault Zone Width [m]


Parameter No. 11
r = 0.0401
Regression Coeff. = 0.0039
Intercept = 0.0091
Total Release (EPASUM)
0.0
0.05
0.10
0.15
0.2
0.4
0.6
0.8
1.0
NW Fault Displacement[m]

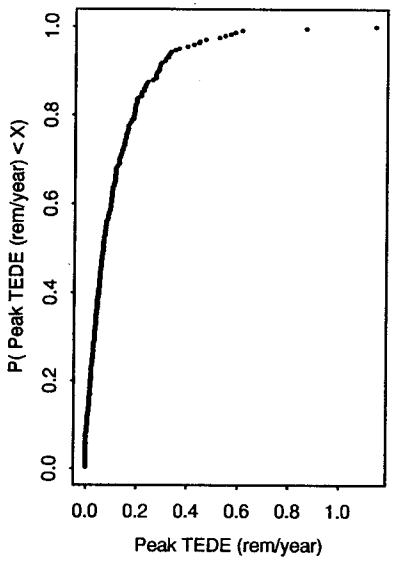

Parameter No. 12
r = -0.0595
Regression Coeff. = -0.006
Intercept = 0.0117
Total Release (EPASUM)
0.0
0.05
0.10
0.15
0.2
0.4
0.6
0.8
1.0
NE Fault Displacement[m]

5 km Scenario
Summary Plots for Peak TEDE (rem/year)

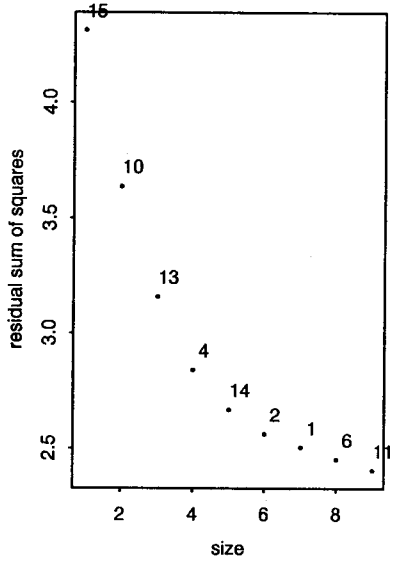
Frequency Distribution



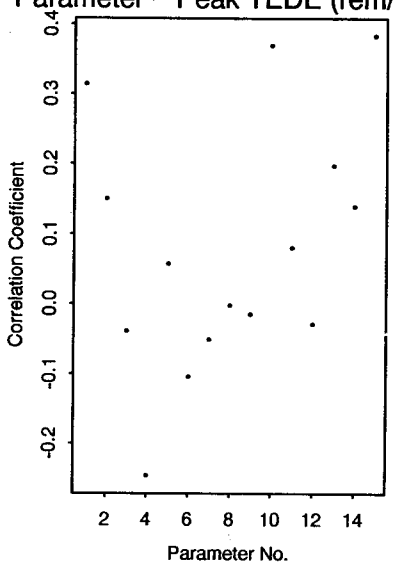
Cumulative Frequency



Stepwise Reduction in Error



Correlation Coefficients
Parameter ~ Peak TEDE (rem/year)



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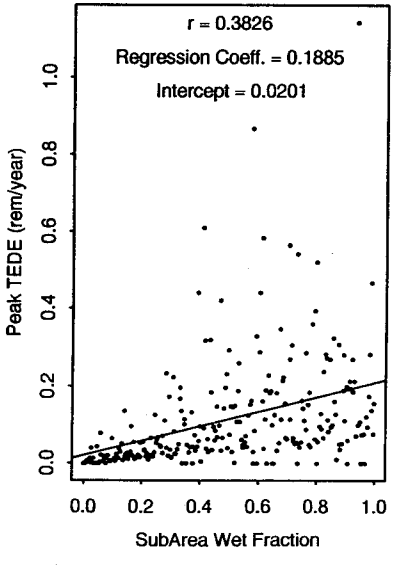

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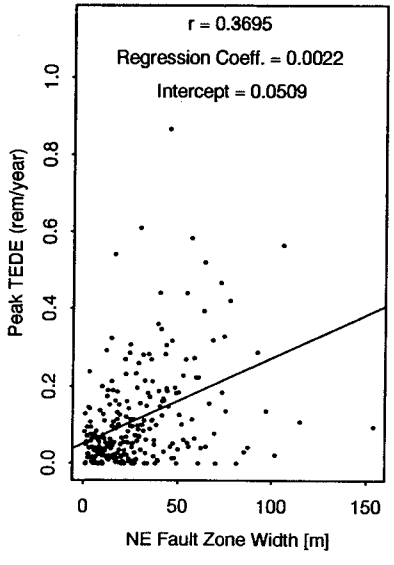

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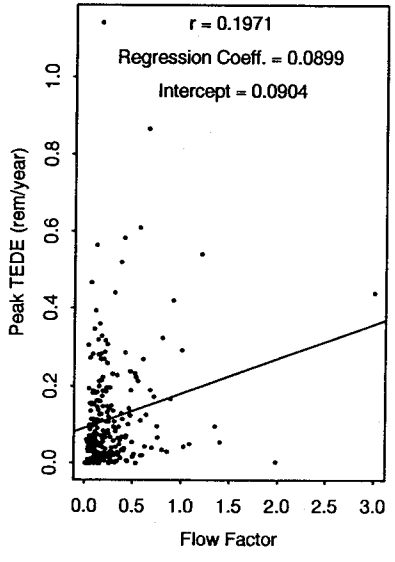

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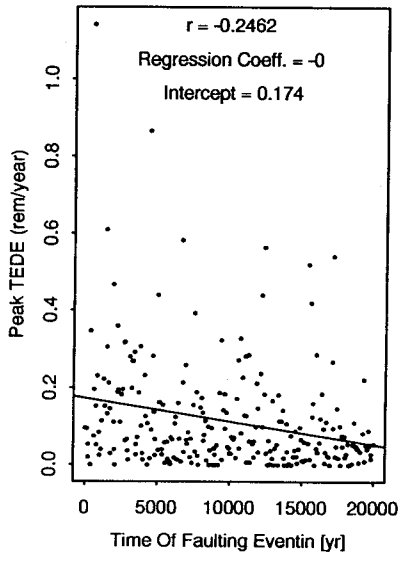

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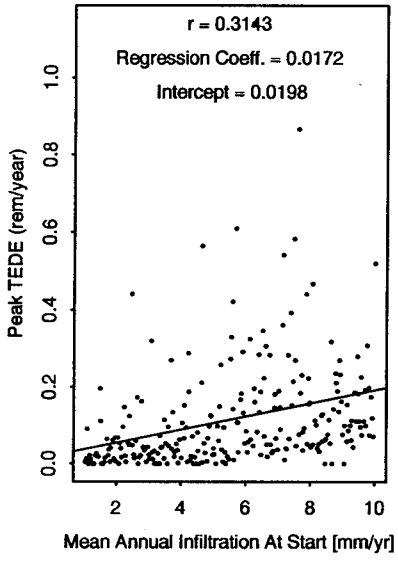

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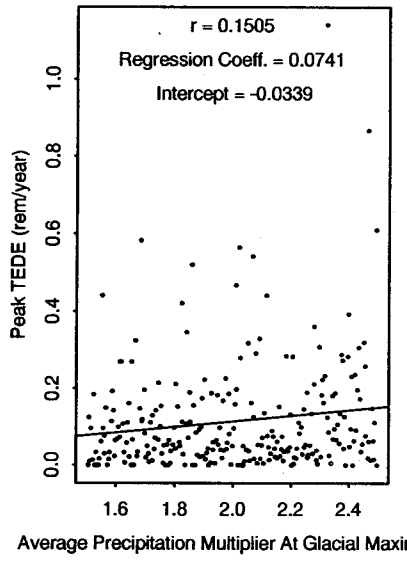

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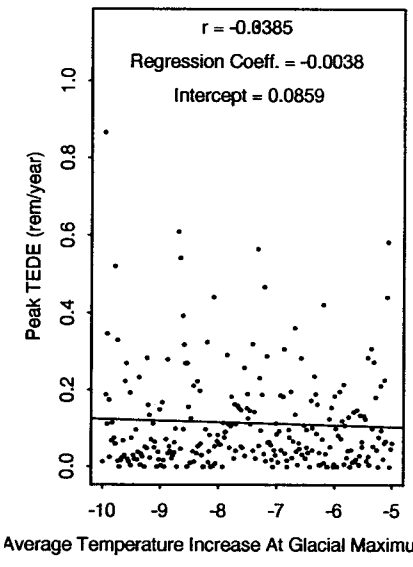

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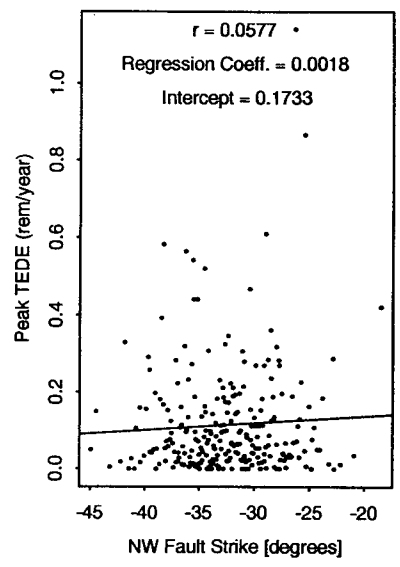

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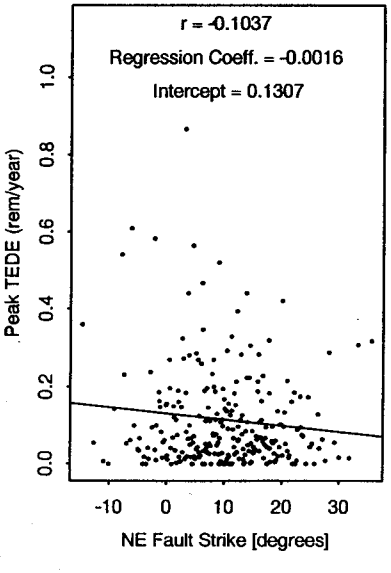

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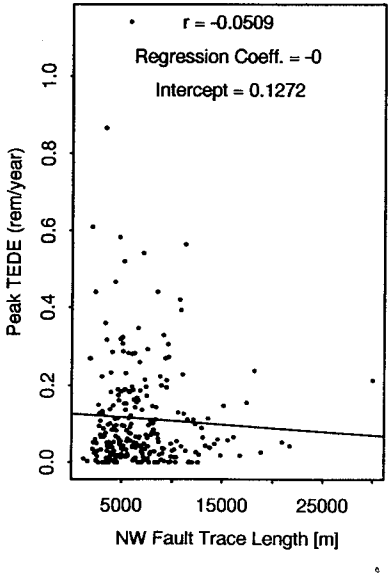

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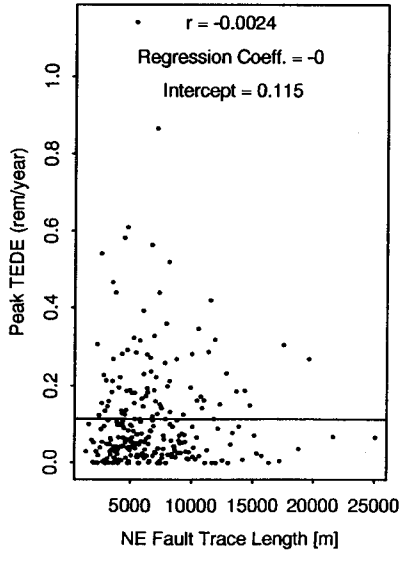

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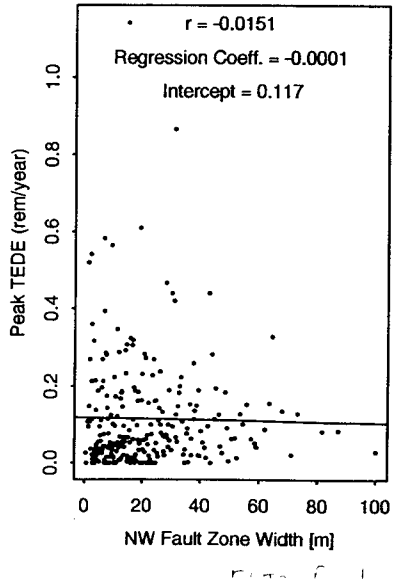

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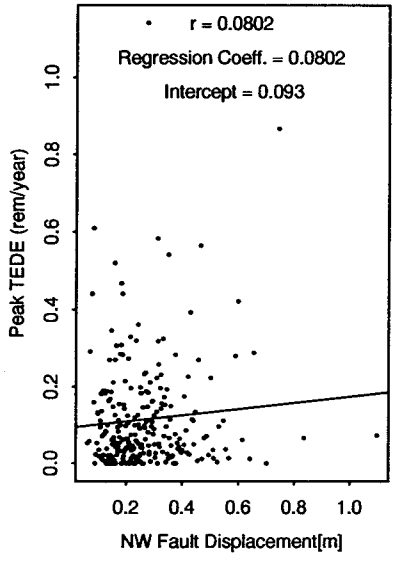

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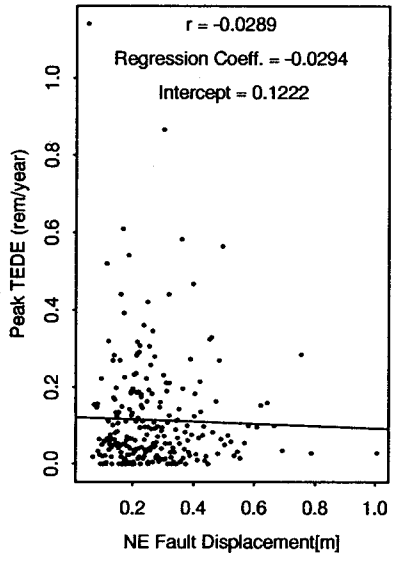

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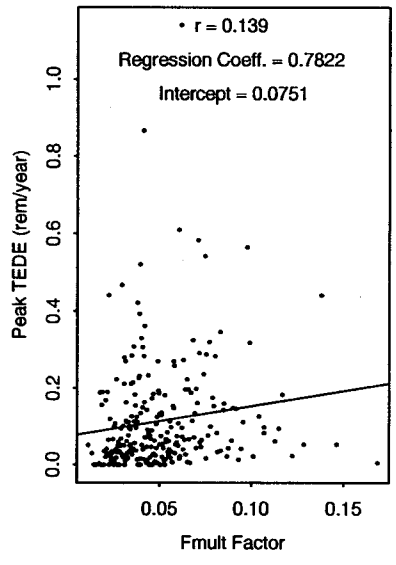
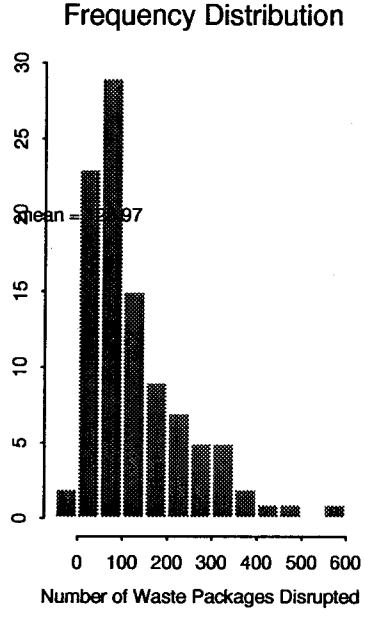


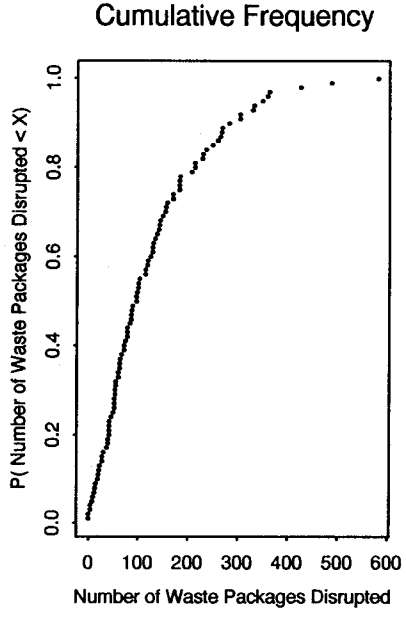
APPENDIX C:

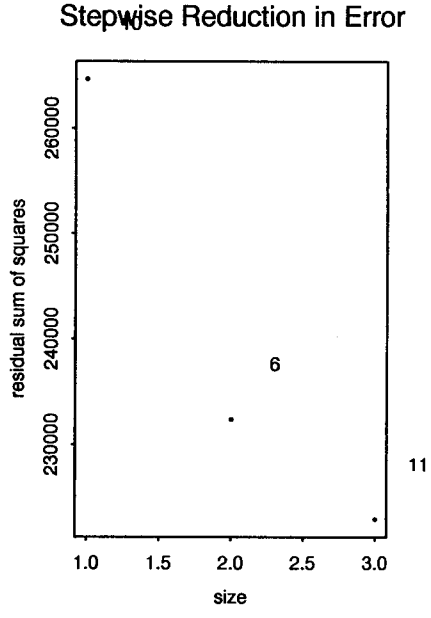
Run: FLTO_Run2

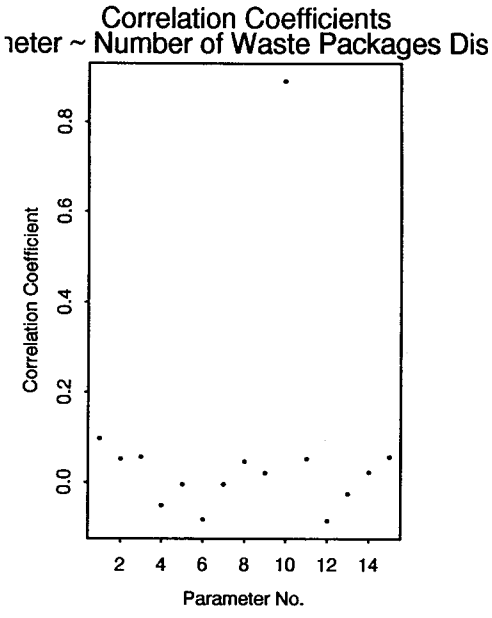
Distance to Focused Group = 5 km
Recurrence Interval = 50,000 years
Only FAULTO with Diffused Corrosion
With Backfill

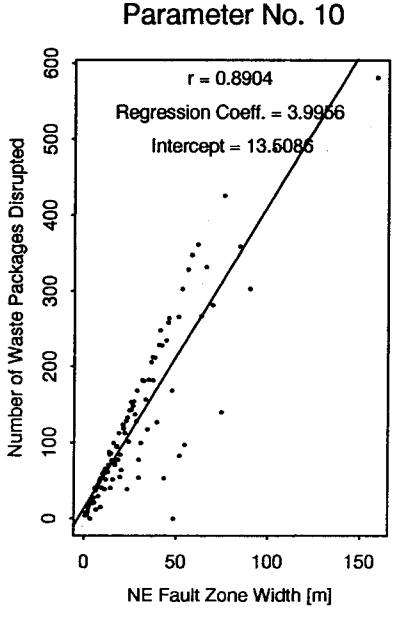
5 km Scenario
Summary Plots for Number of Waste Packages Disrupted

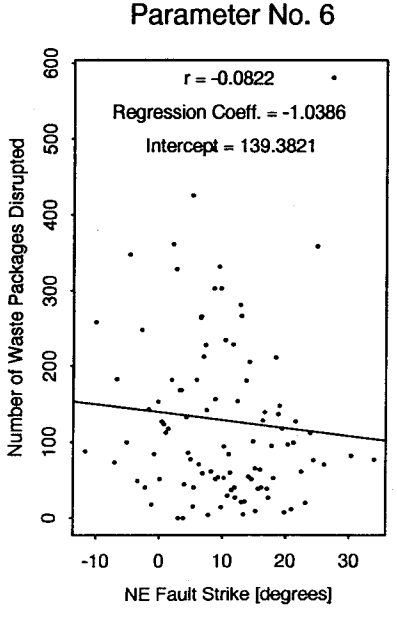


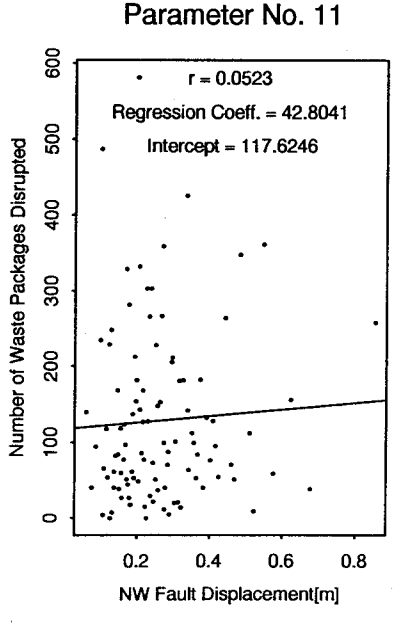


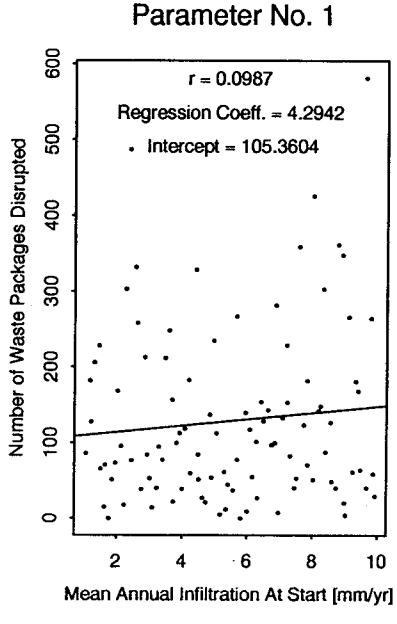












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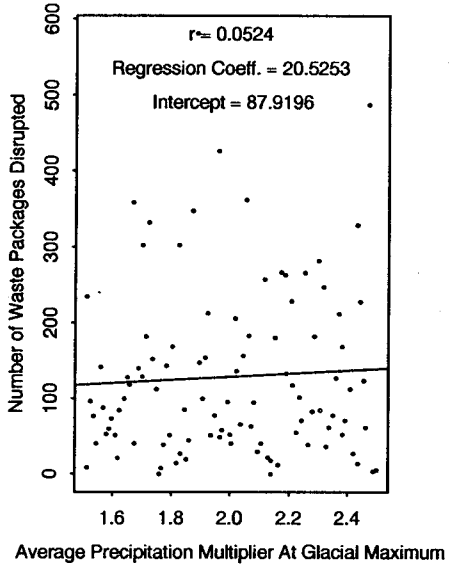

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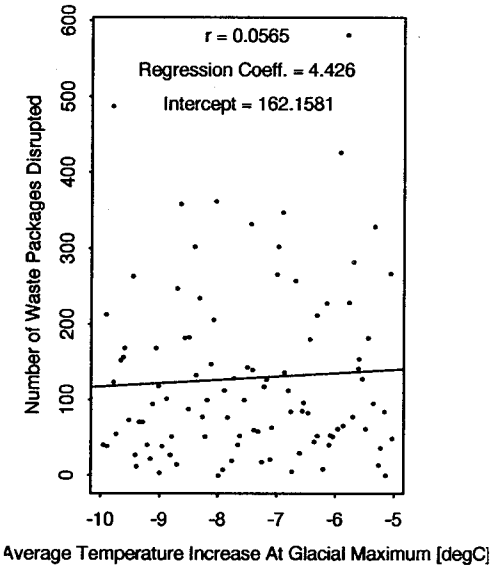

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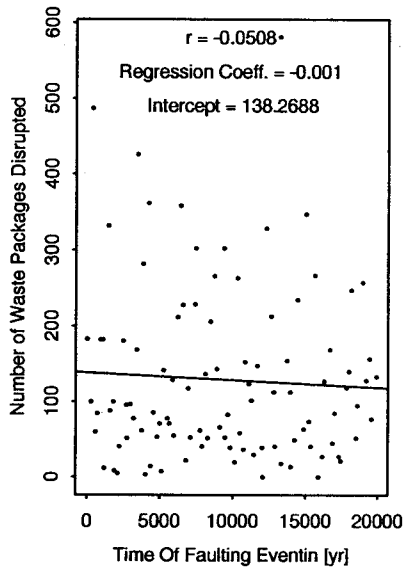

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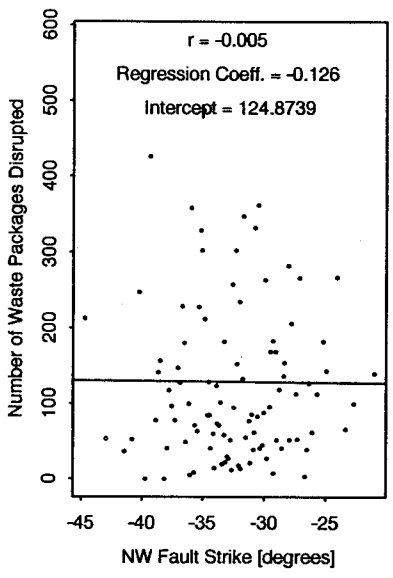

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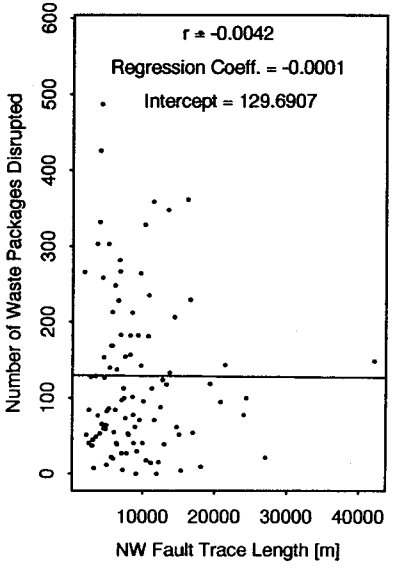

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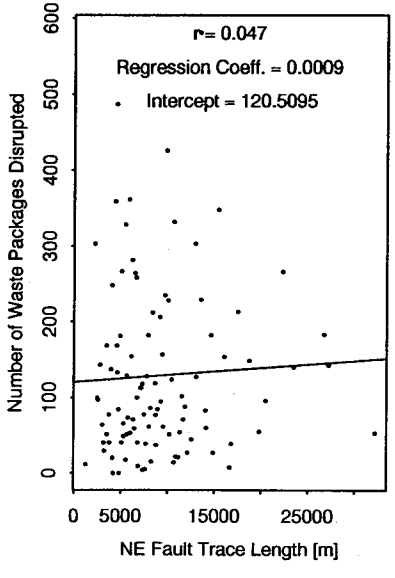

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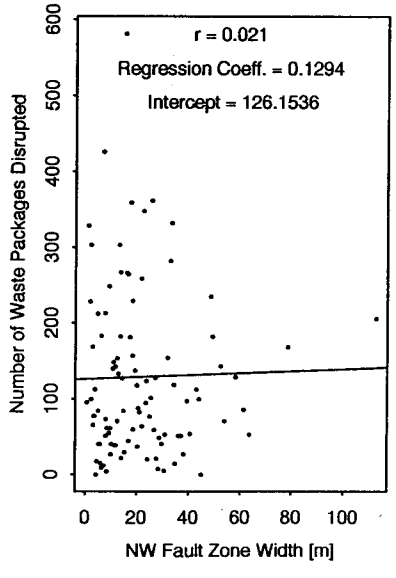

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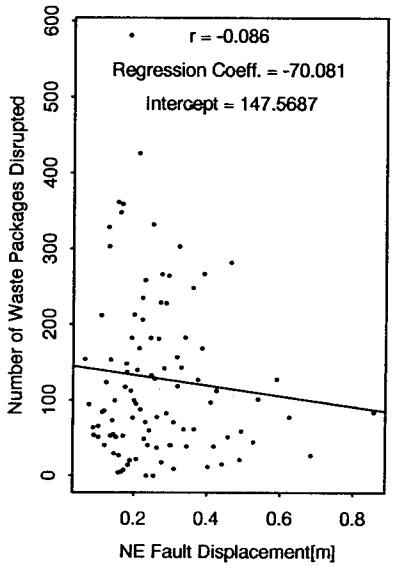
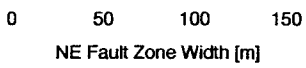
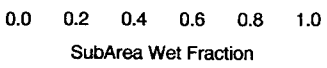
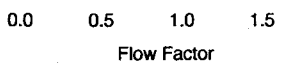
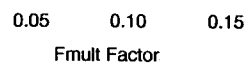




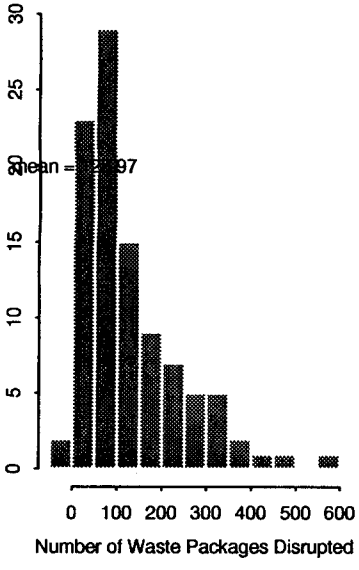




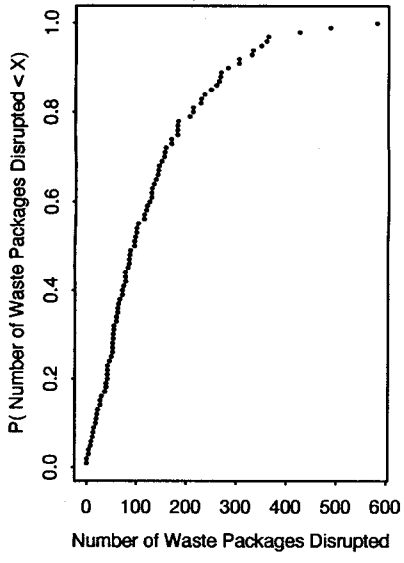


5 km Scenario
Summary Plots for Number of Waste Packages Disrupted

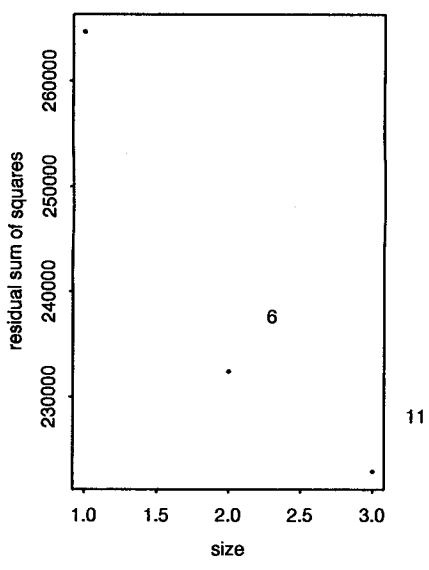
Frequency Distribution



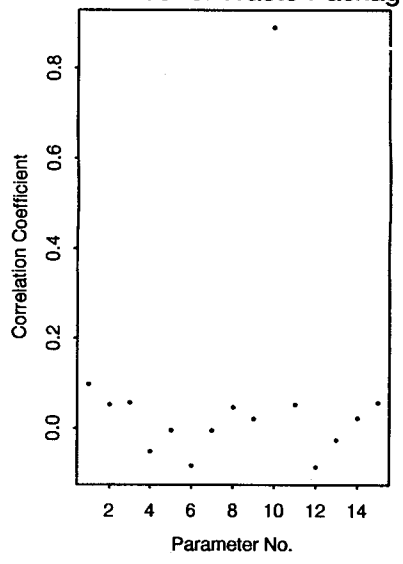
Cumulative Frequency



Stepwise Reduction in Error



Correlation Coefficients



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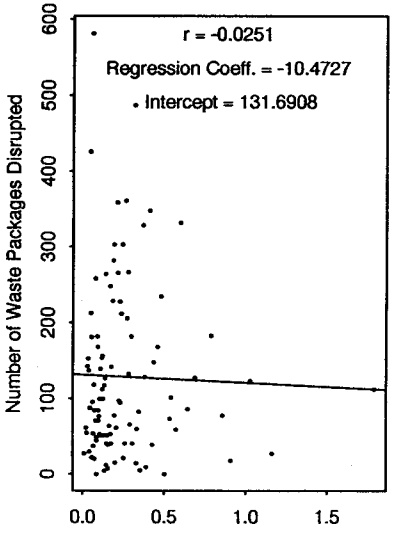

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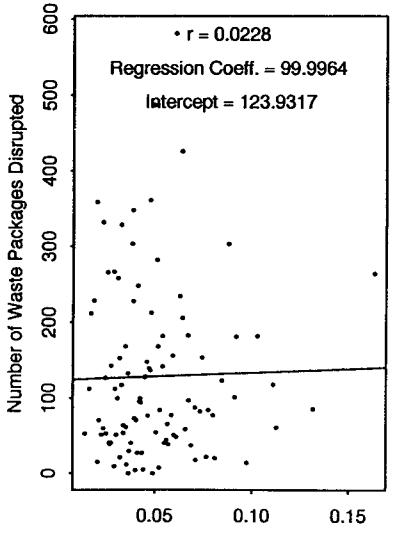

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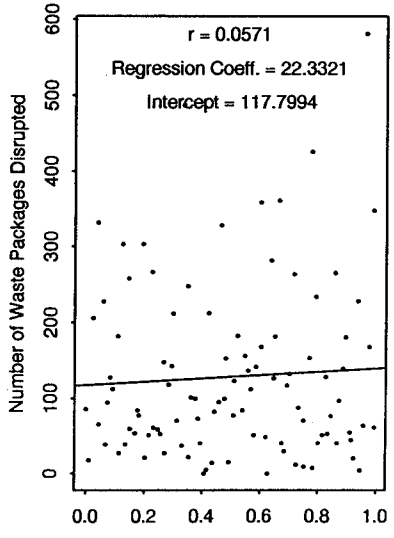
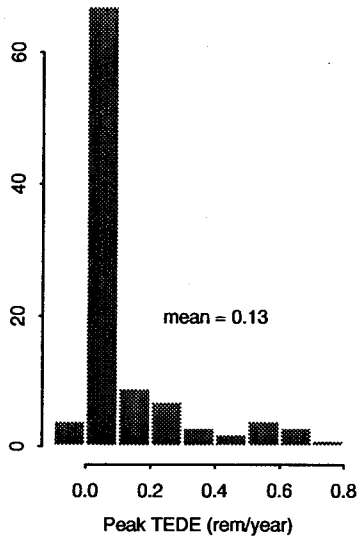


5 km Scenario
Summary Plots for Peak TEDE (rem/year)

Frequency Distribution



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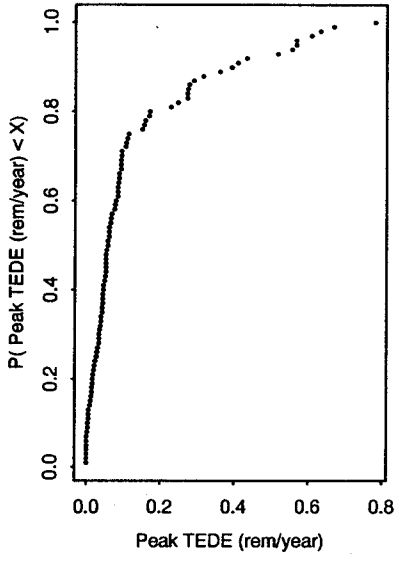
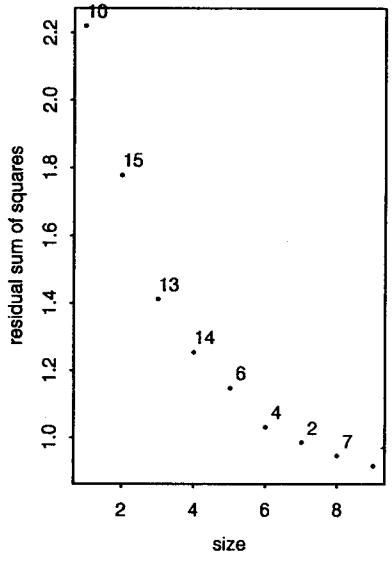
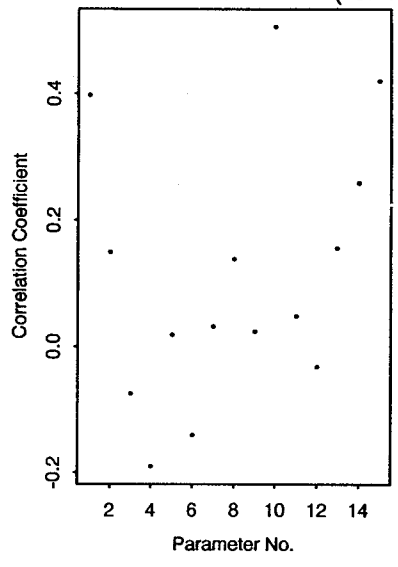


Stepwise Reduction in Error



Correlation Coefficients
Parameter ~ Peak TEDE (rem/year)



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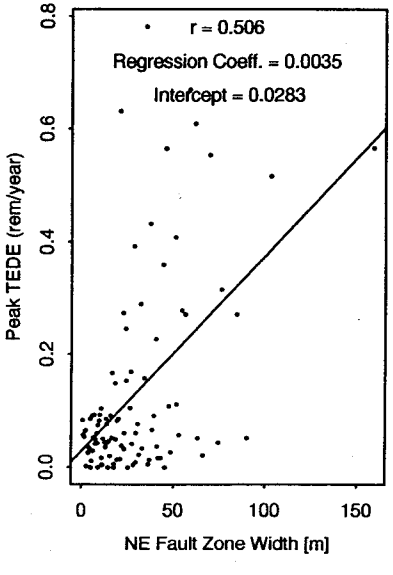

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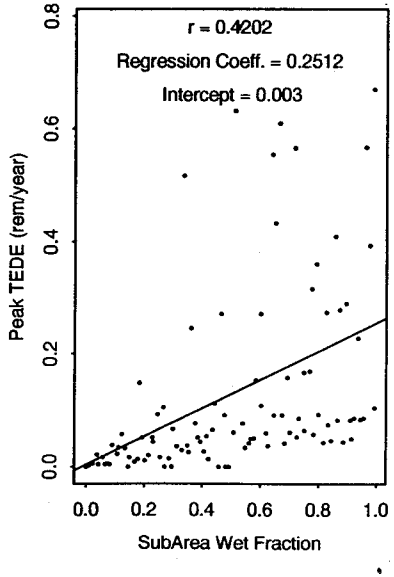

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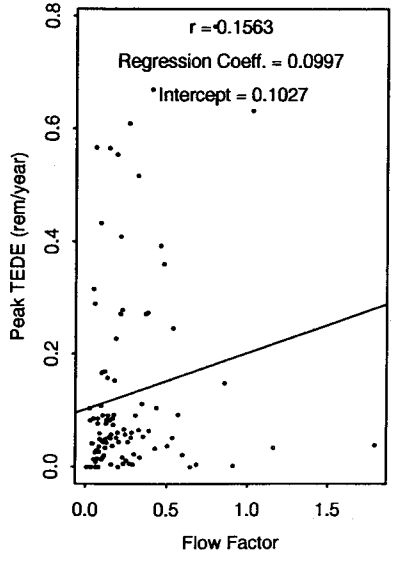

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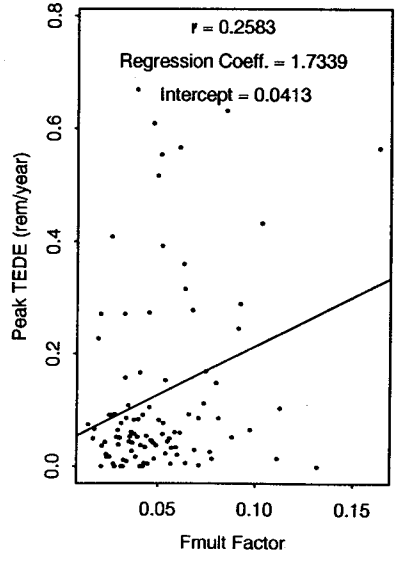

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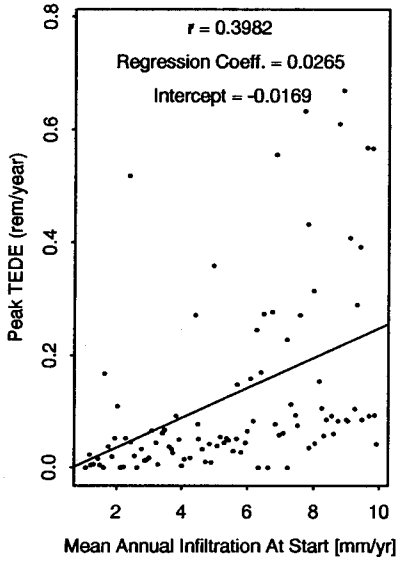

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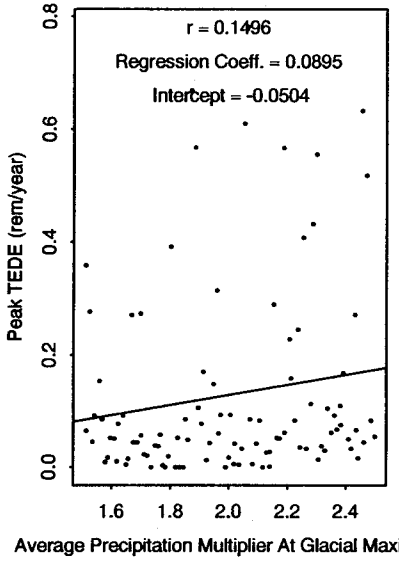

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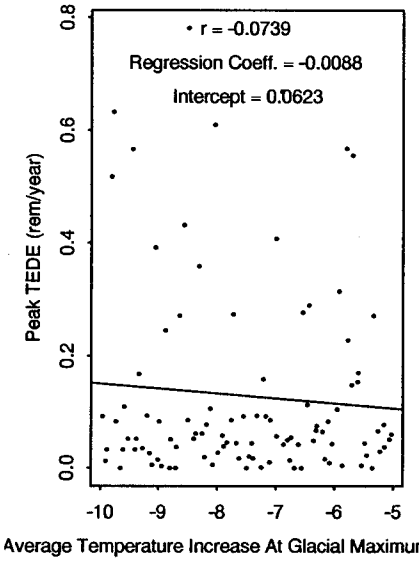

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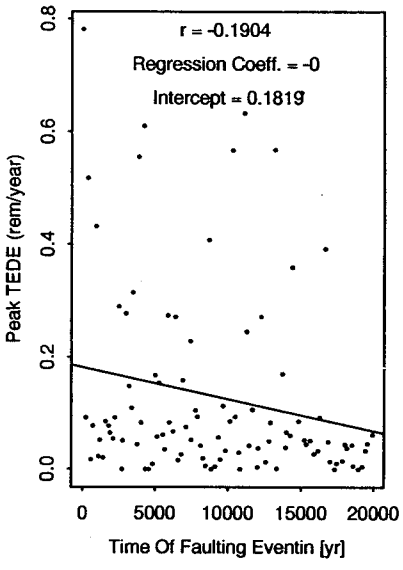

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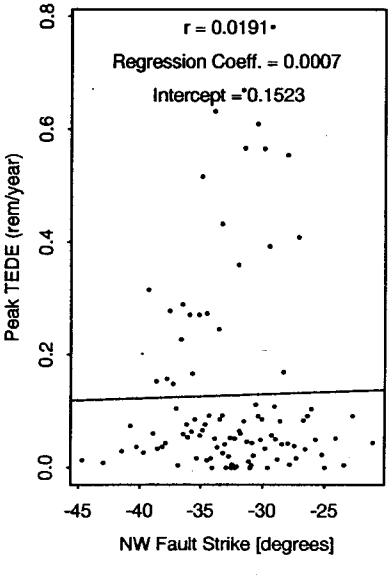
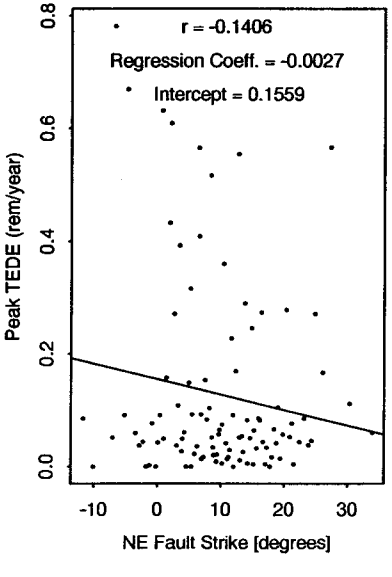
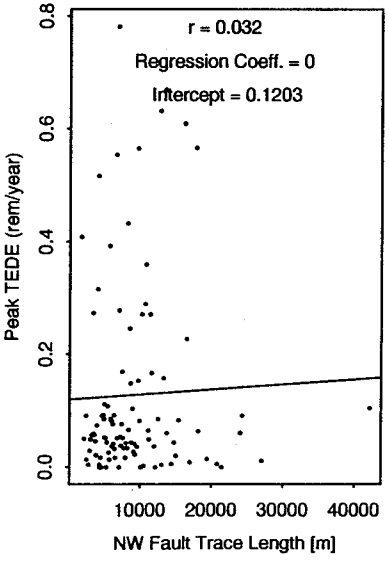


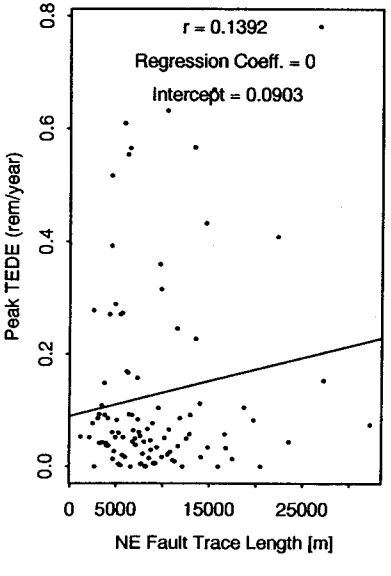
Parameter No. 6



Parameter No. 7

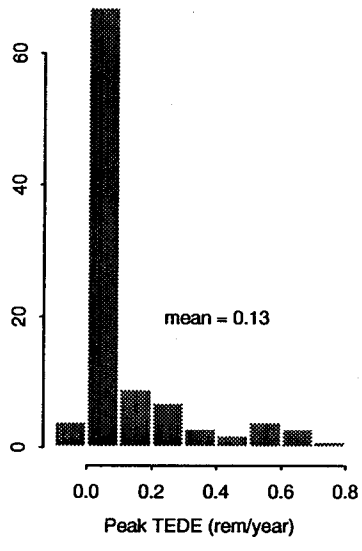


Parameter No. 8

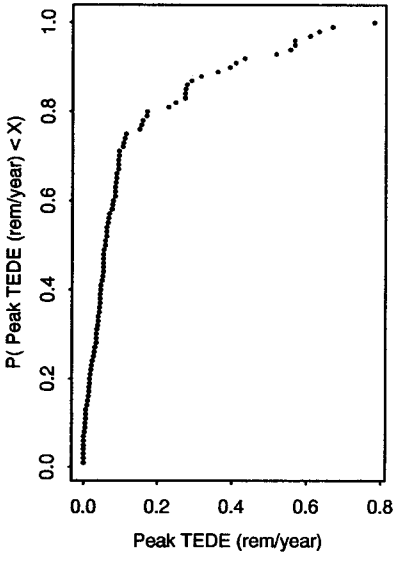


5 km Scenario
Summary Plots for Peak TEDE (rem/year)

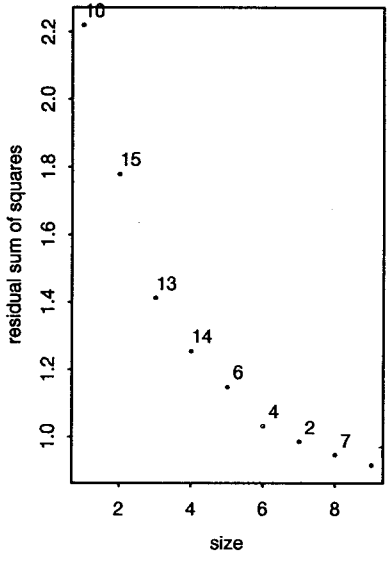
Frequency Distribution



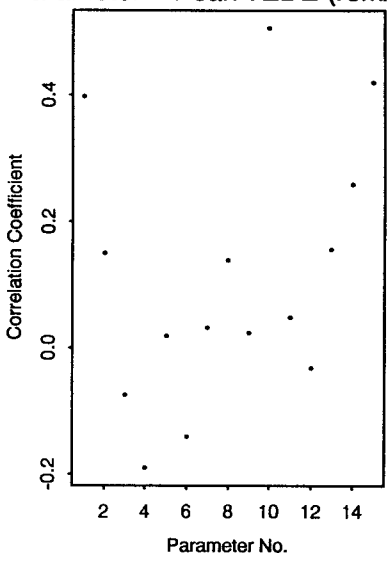
Cumulative Frequency



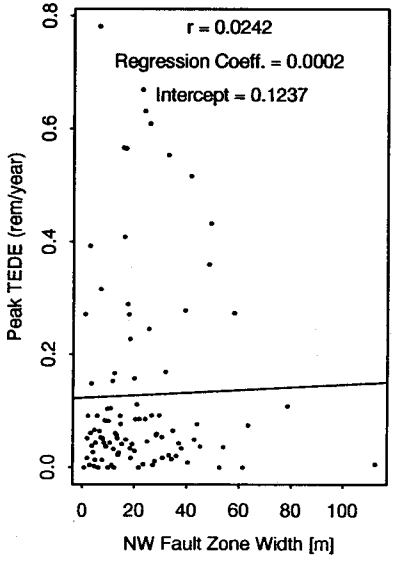
Stepwise Reduction in Error



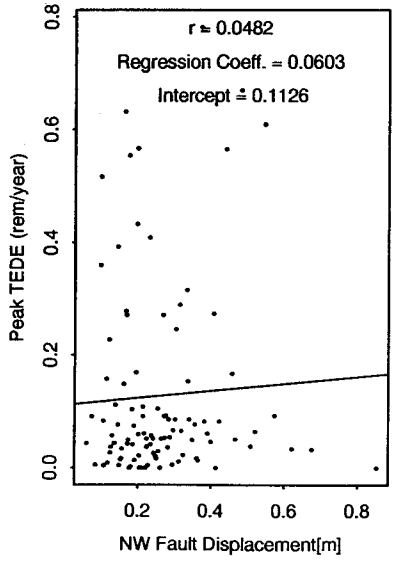
Correlation Coefficients
Parameter ~ Peak TEDE (rem/year)



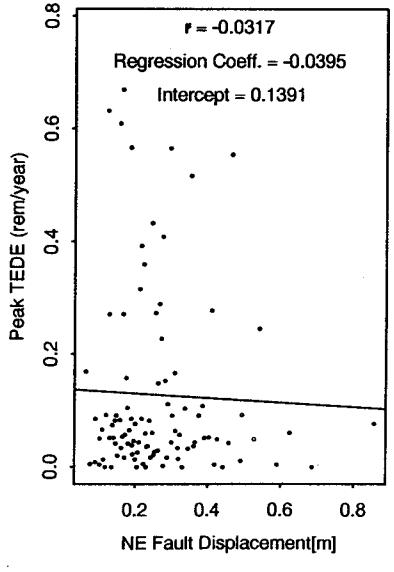
Parameter No. 9



Parameter No. 11

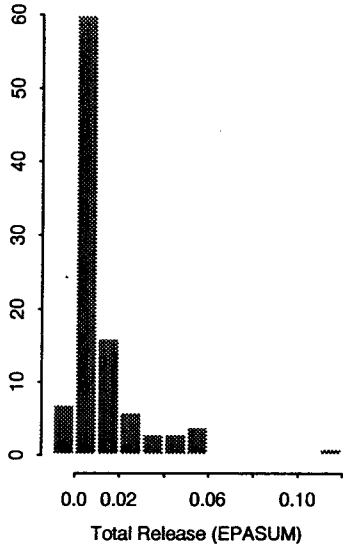


Parameter No. 12

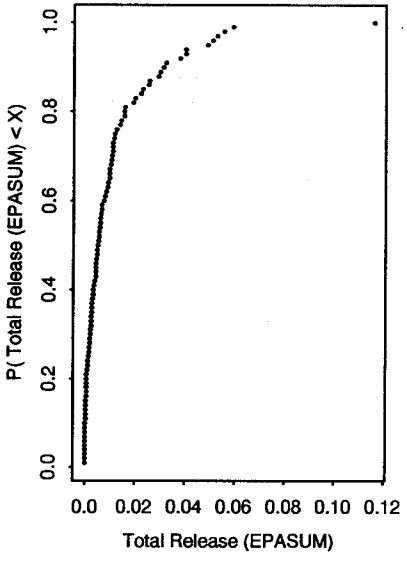


5 km Scenario
Summary Plots for Total Release (EPASUM)

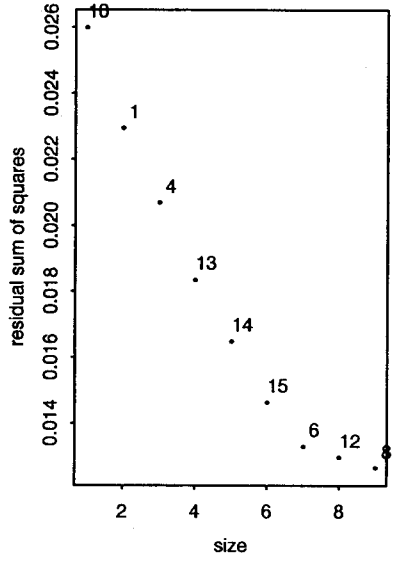
Frequency Distribution



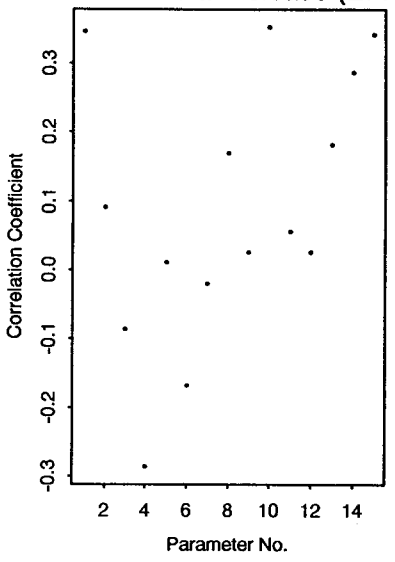
Cumulative Frequency



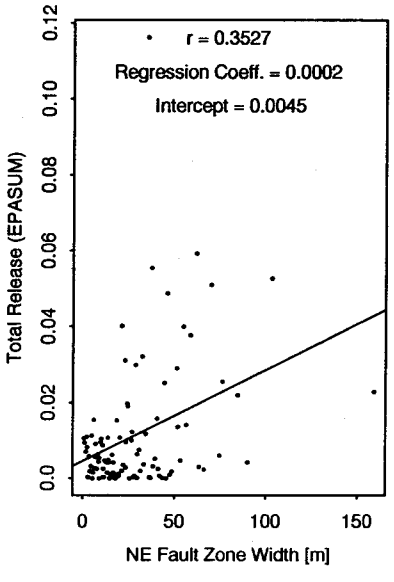
Stepwise Reduction in Error



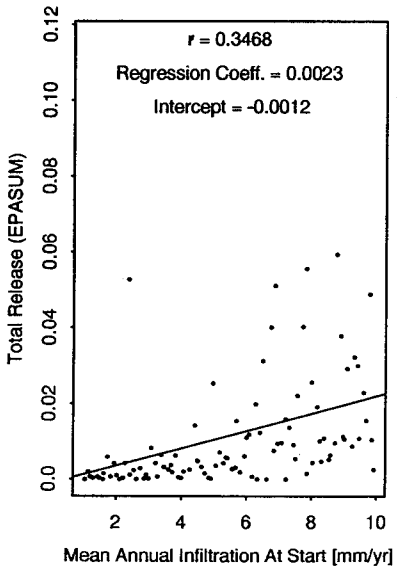
Correlation Coefficients
Parameter ~ Total Release (EPASUM)



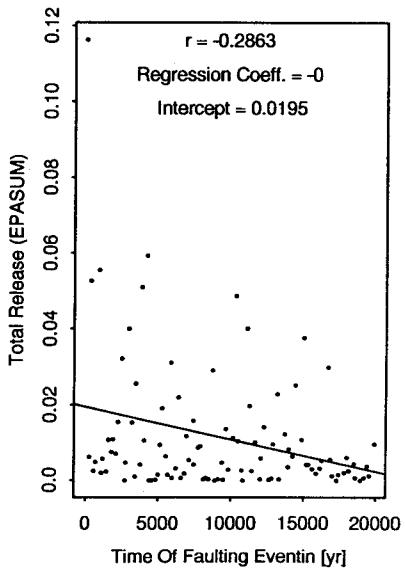
Parameter No. 10



Parameter No. 1



Parameter No. 4



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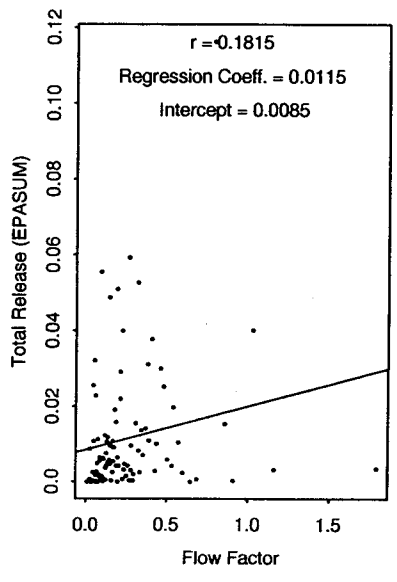
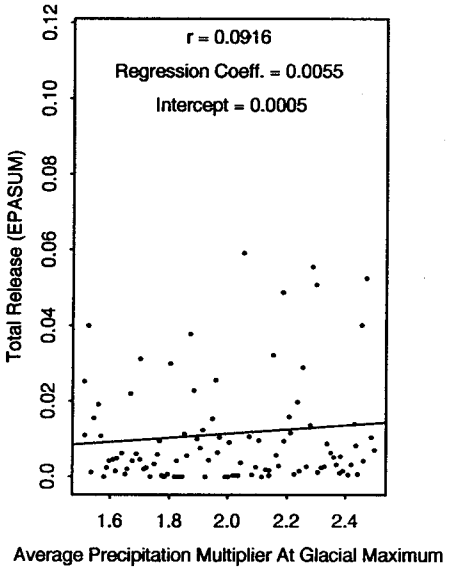
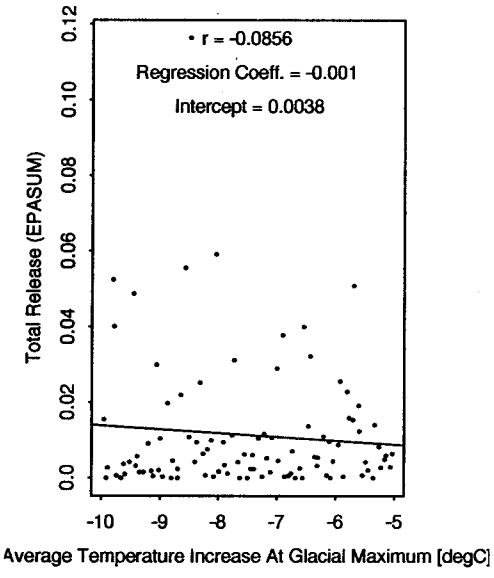


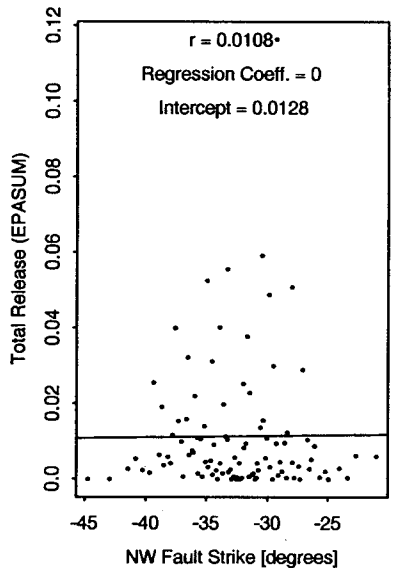
Parameter No. 2



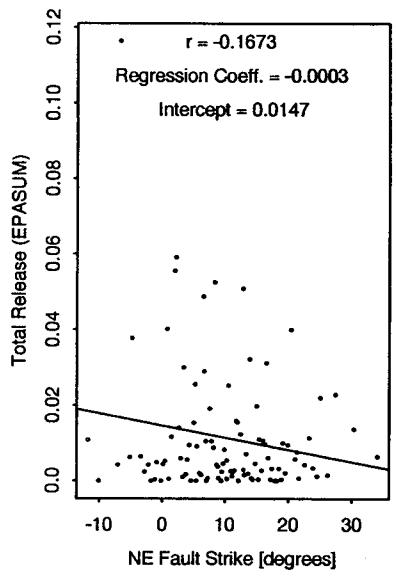
Parameter No. 3



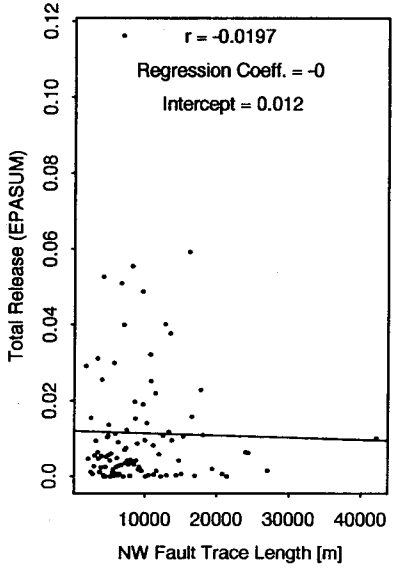
Parameter No. 5



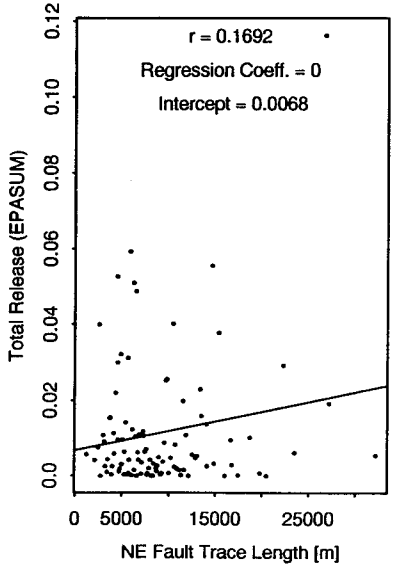
Parameter No. 6



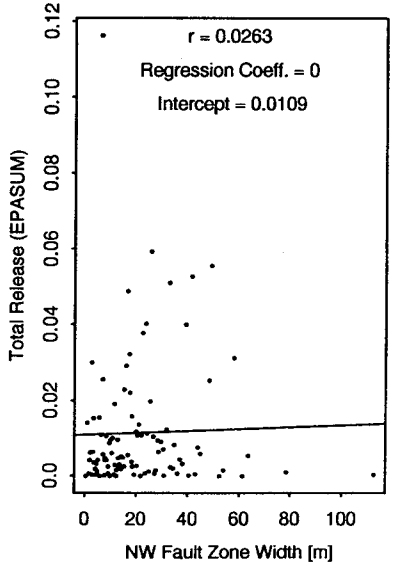
Parameter No. 7



Parameter No. 8



Parameter No. 9



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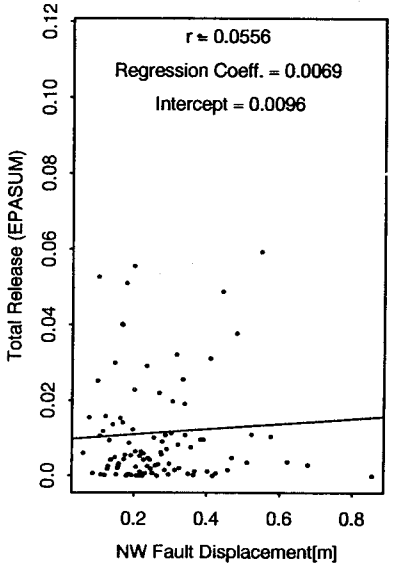
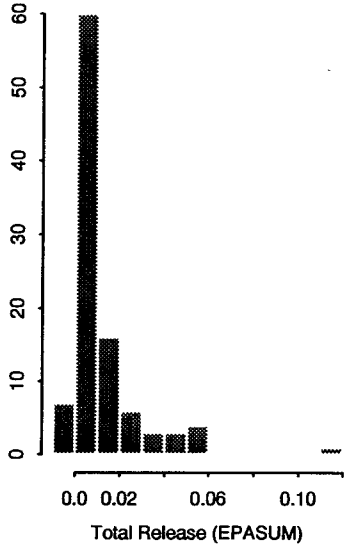


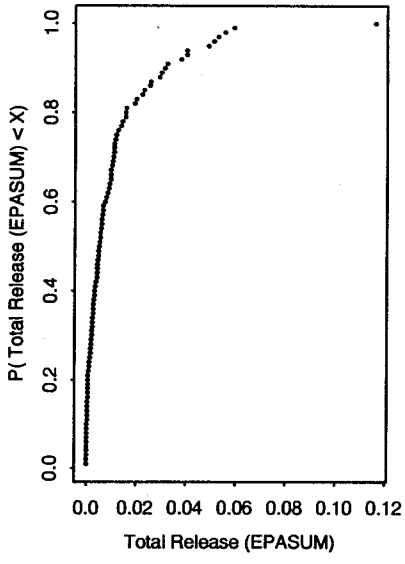
TOP RUN2

5 km Scenario
Summary Plots for Total Release (EPASUM)

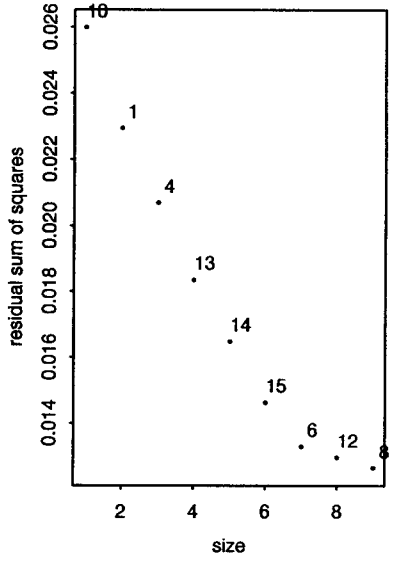
Frequency Distribution



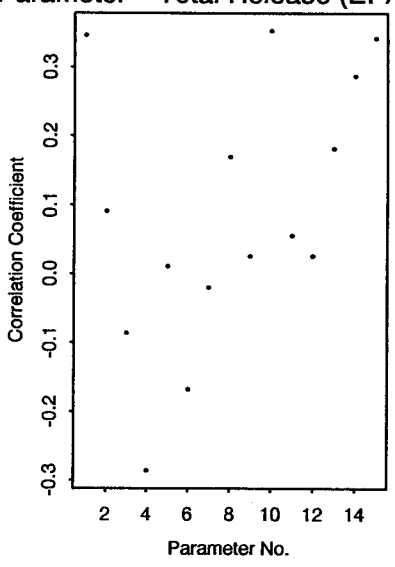
Cumulative Frequency



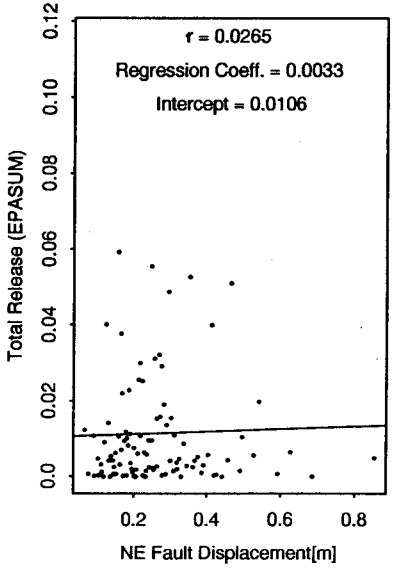
Stepwise Reduction in Error



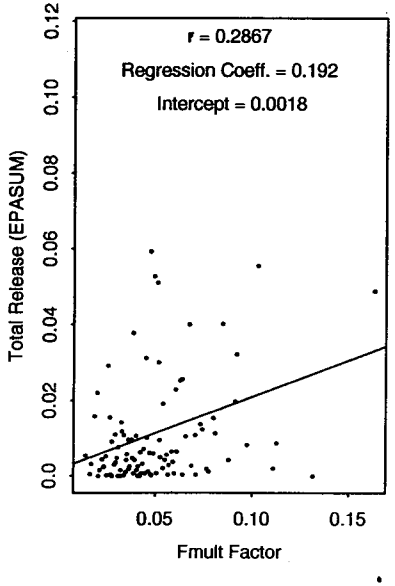
Correlation Coefficients
Parameter ~ Total Release (EPASUM)



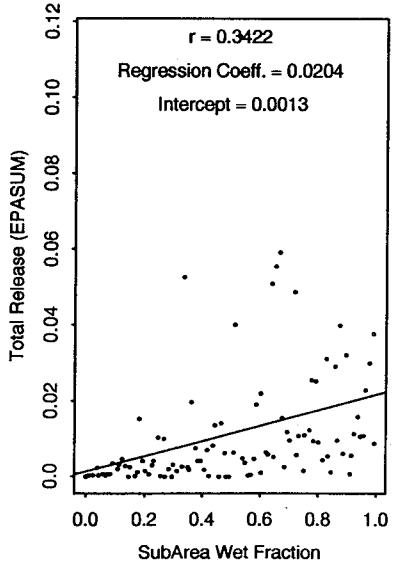
Parameter No. 12



Parameter No. 14



Parameter No. 15



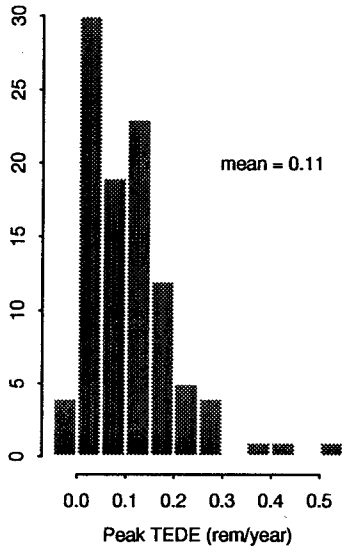
APPENDIX D:

Run: FLTO_Run3

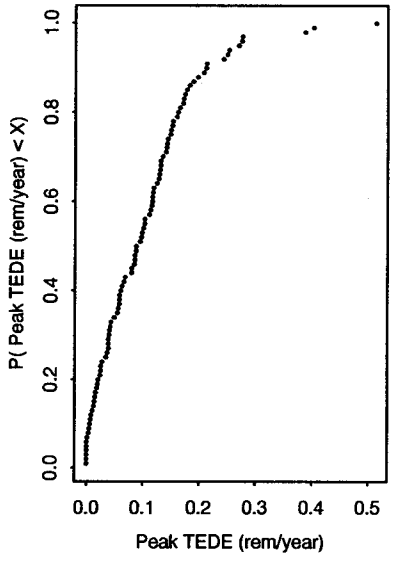
Distance to Focused Group = 5 km
Only SEISMO with Diffused Corrosion
With Backfill

5 km Scenario
Summary Plots for Peak TEDE (rem/year)

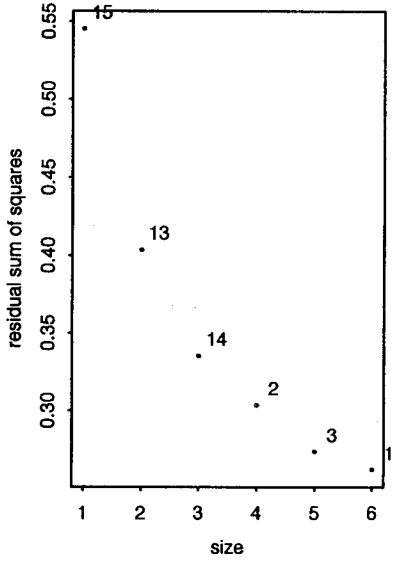
Frequency Distribution



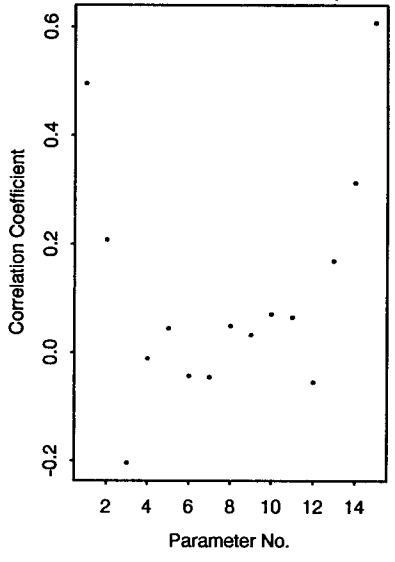
Cumulative Frequency



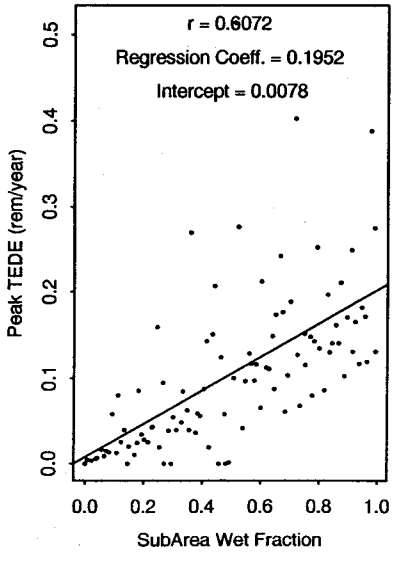
Stepwise Reduction in Error



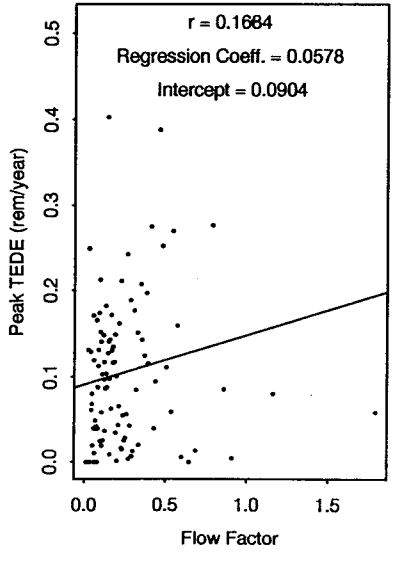
Correlation Coefficients
Parameter ~ Peak TEDE (rem/year)



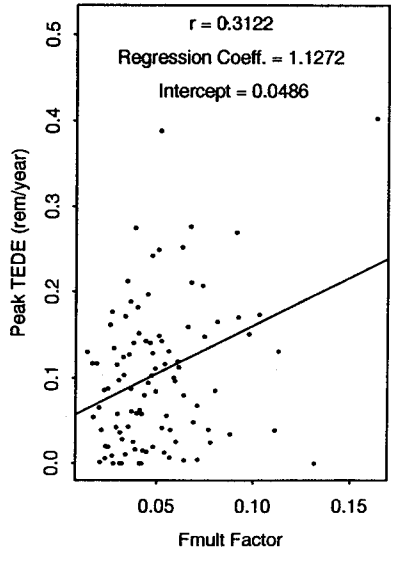
Parameter No. 15



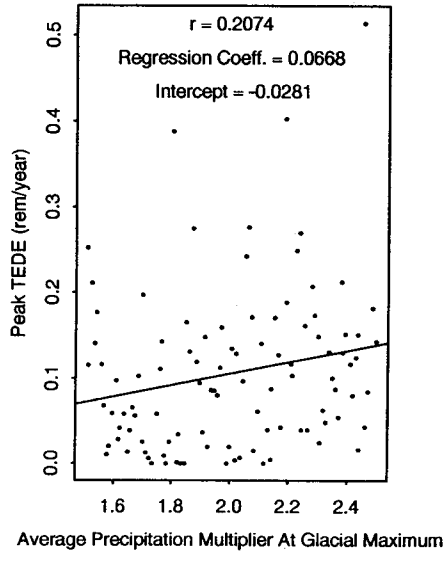
Parameter No. 13



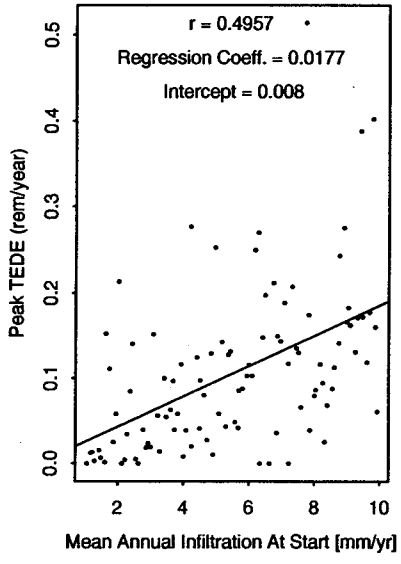
Parameter No. 14



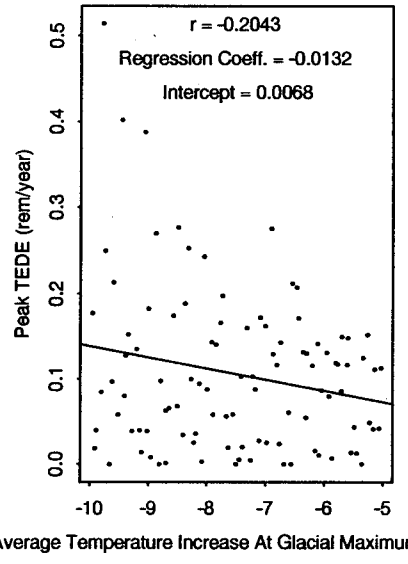
Parameter No. 2



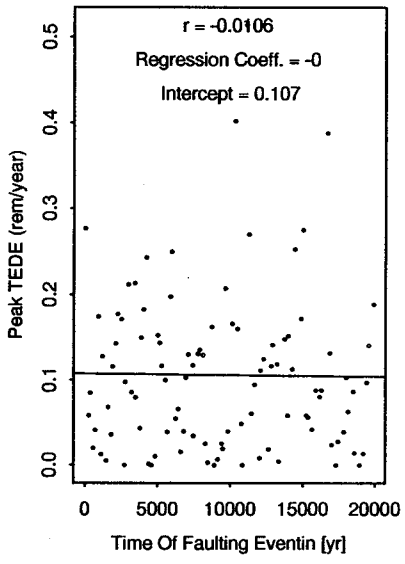
Parameter No. 1



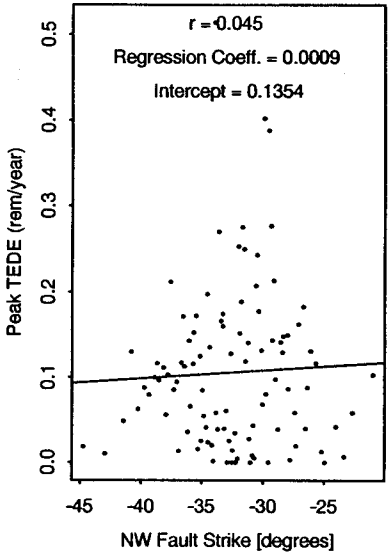
Parameter No. 3



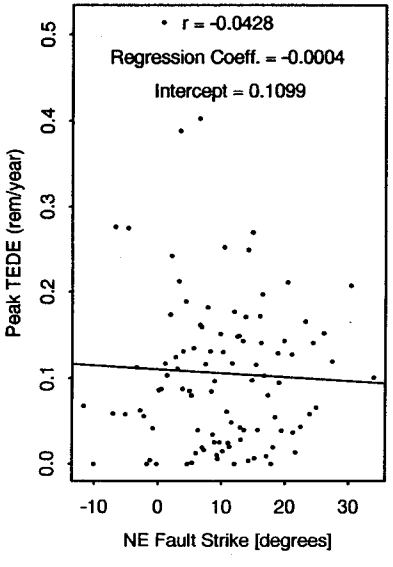
Parameter No. 4



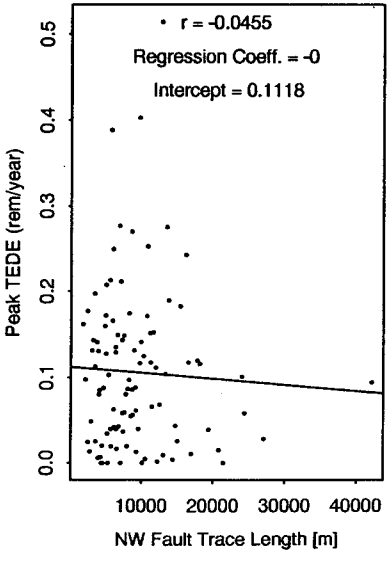
Parameter No. 5



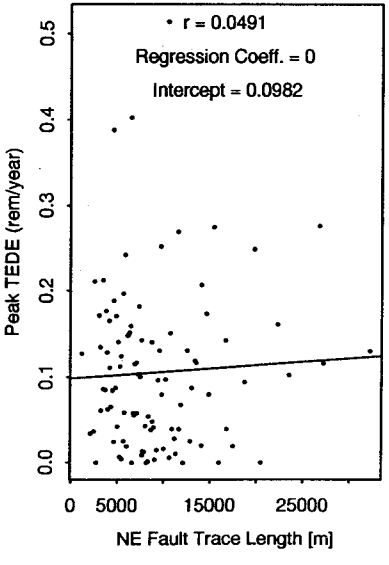
Parameter No. 6



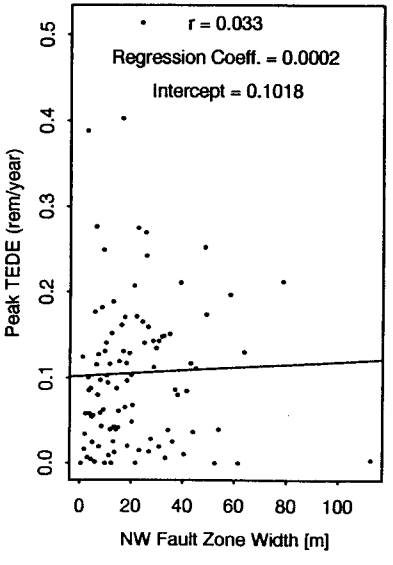
Parameter No. 7



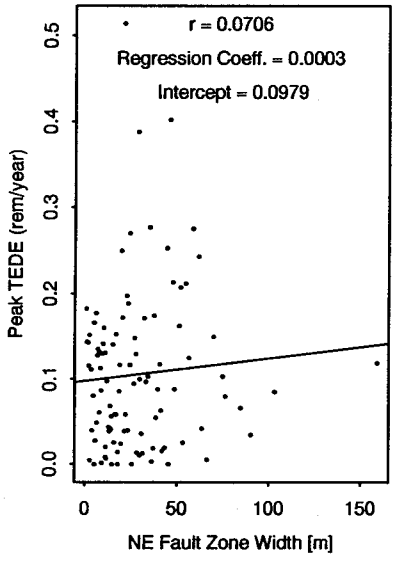
Parameter No. 8



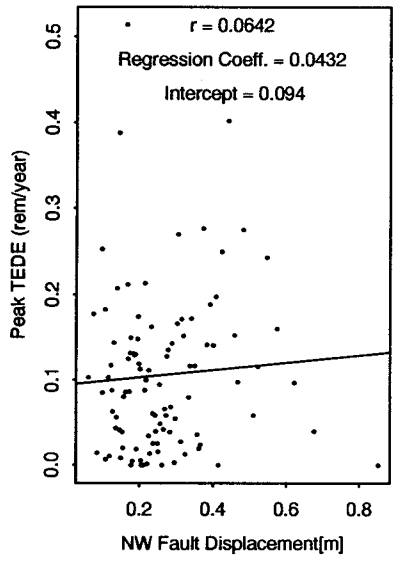
Parameter No. 9



Parameter No. 10



Parameter No. 11



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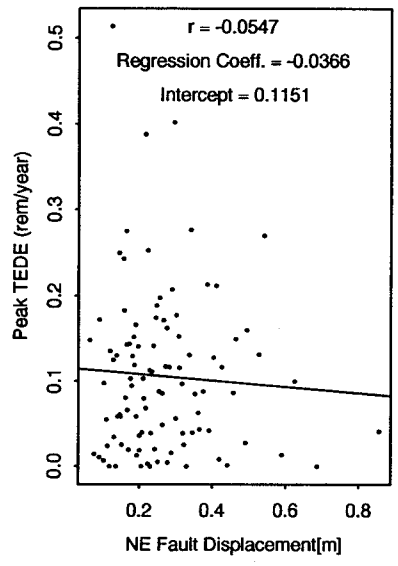
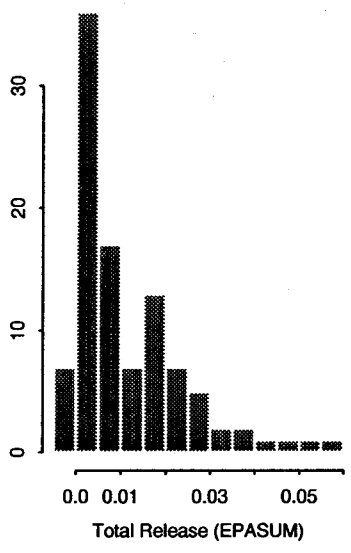
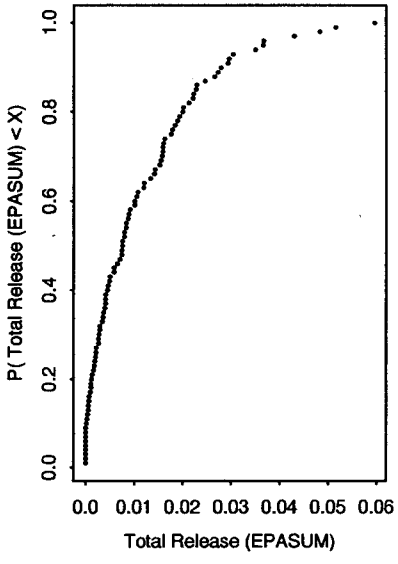


5 km Scenario
Summary Plots for Total Release (EPASUM)

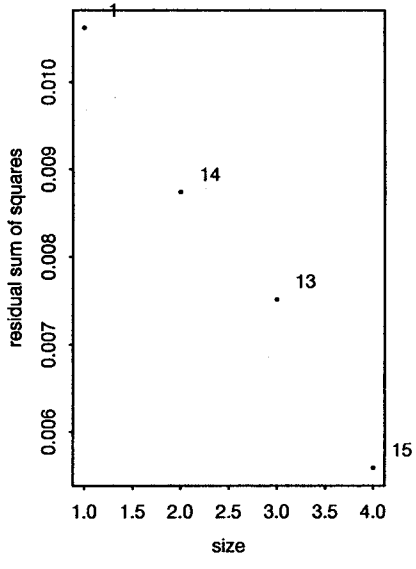
Frequency Distribution



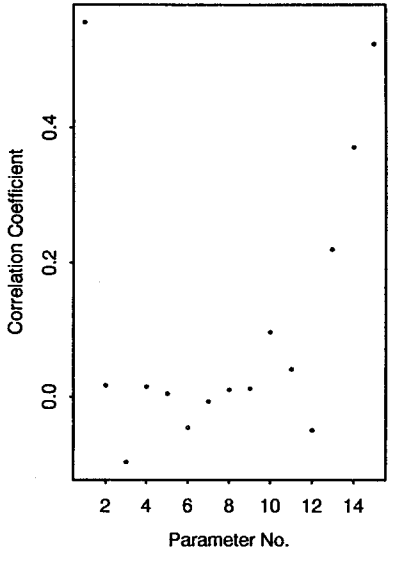
Cumulative Frequency



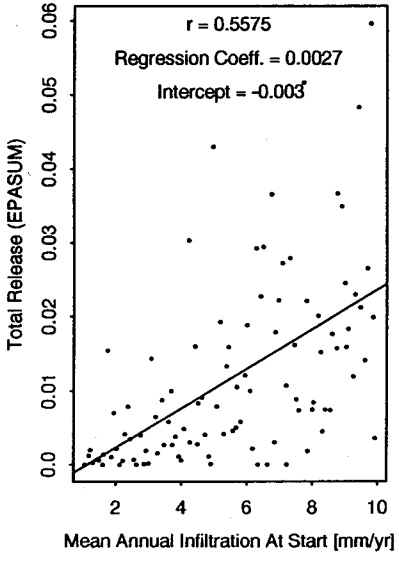
Stepwise Reduction in Error



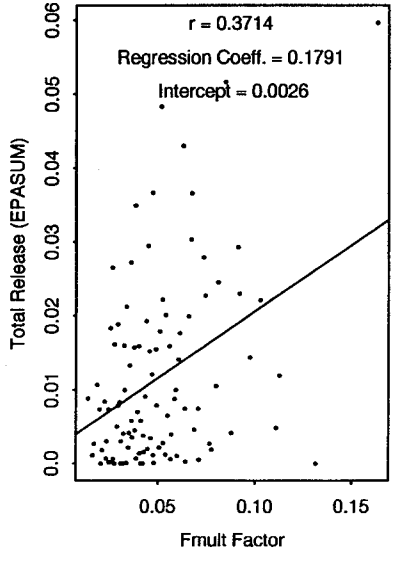
Correlation Coefficients
Parameter ~ Total Release (EPASUM)



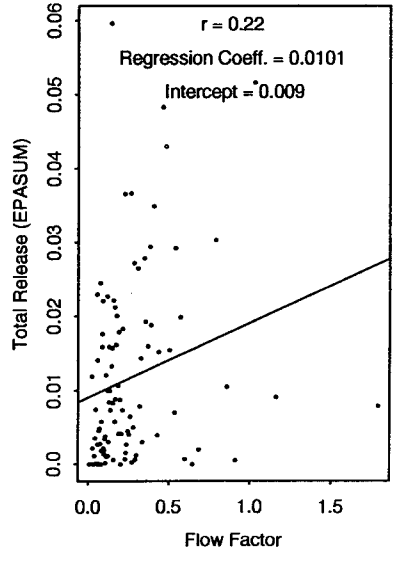
Parameter No. 1



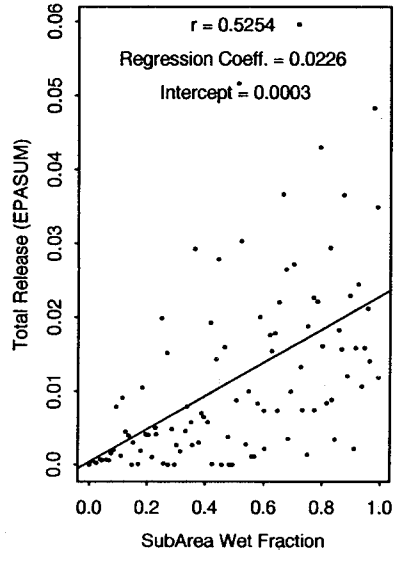
Parameter No. 14



Parameter No. 13



Parameter No. 15



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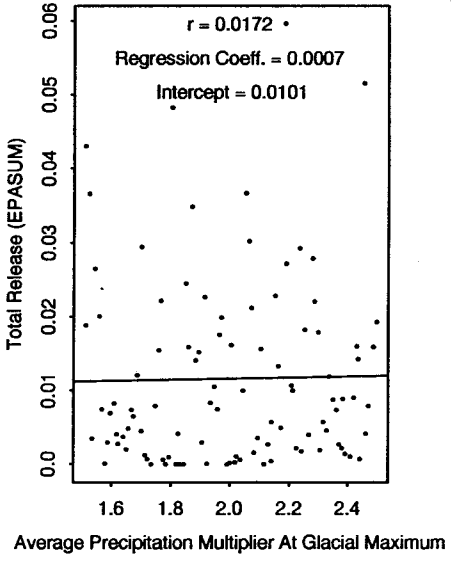

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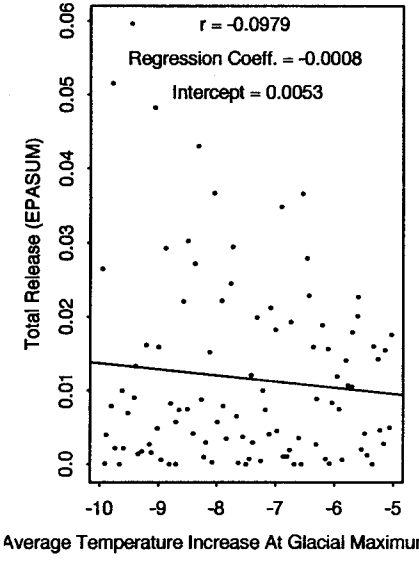

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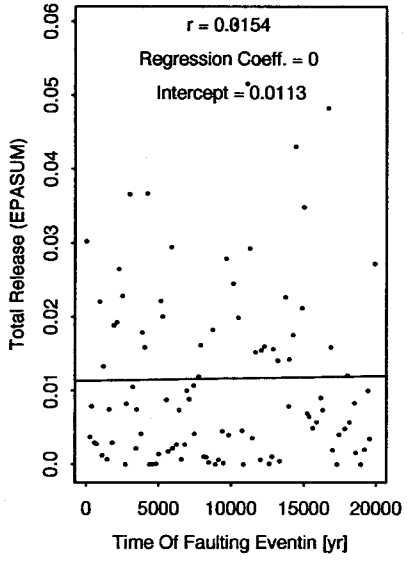

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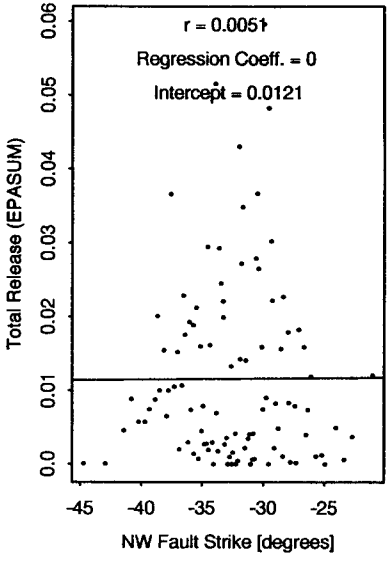

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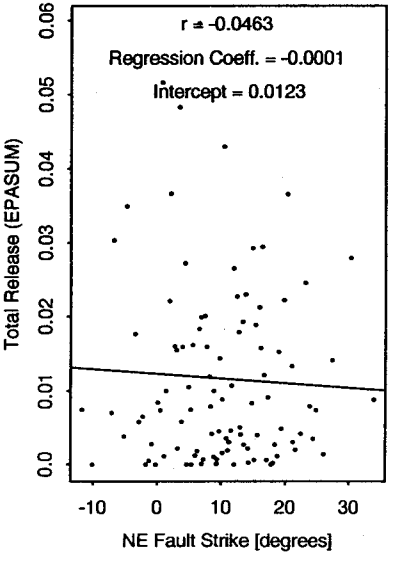

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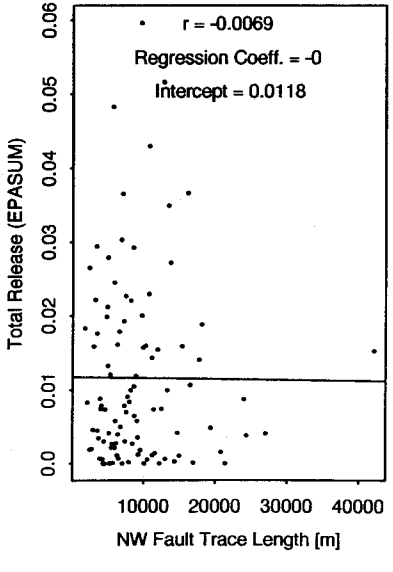
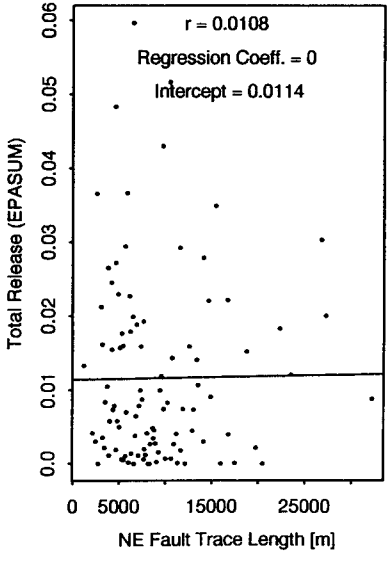
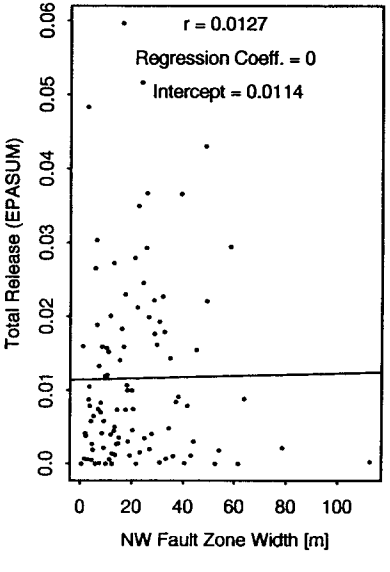


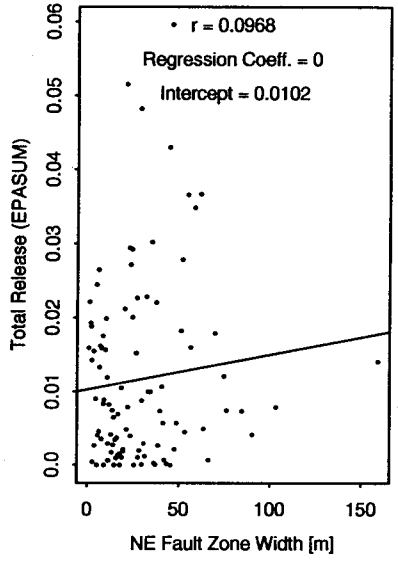
Parameter No. 8



Parameter No. 9



Parameter No. 10



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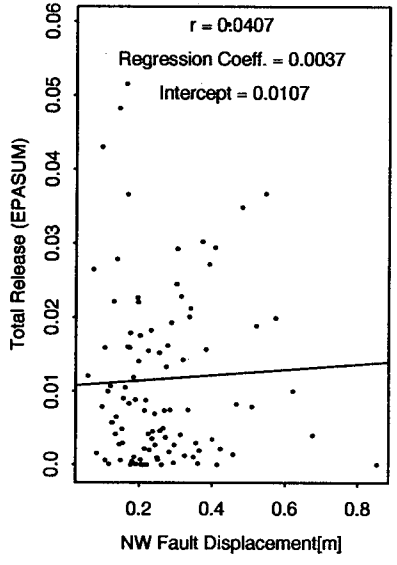

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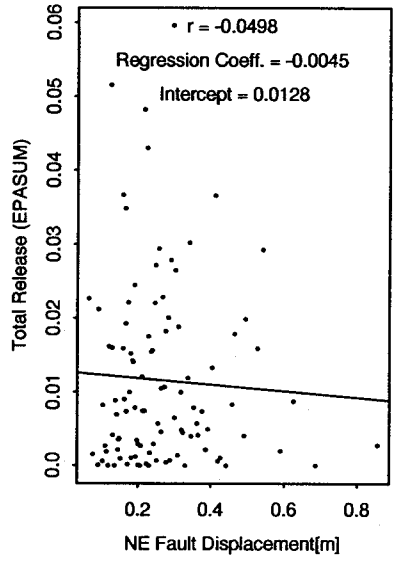
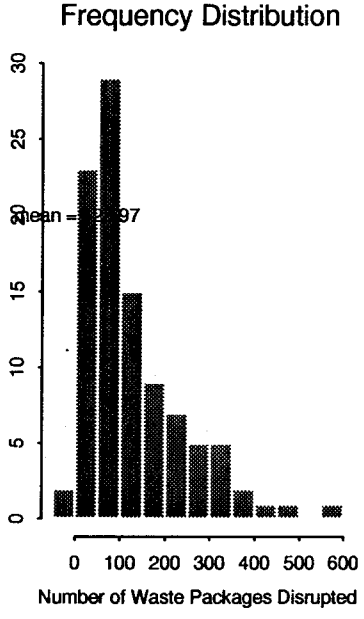


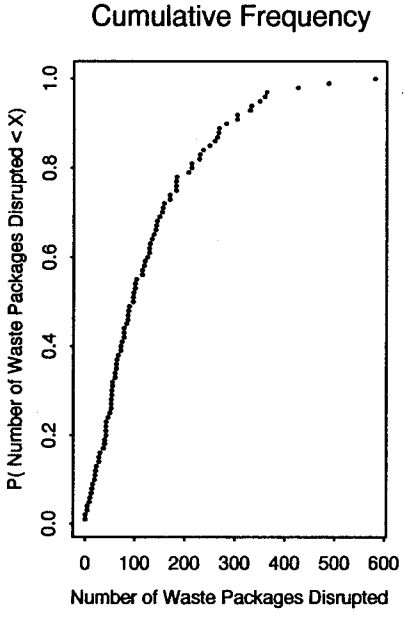
APPENDIX E:

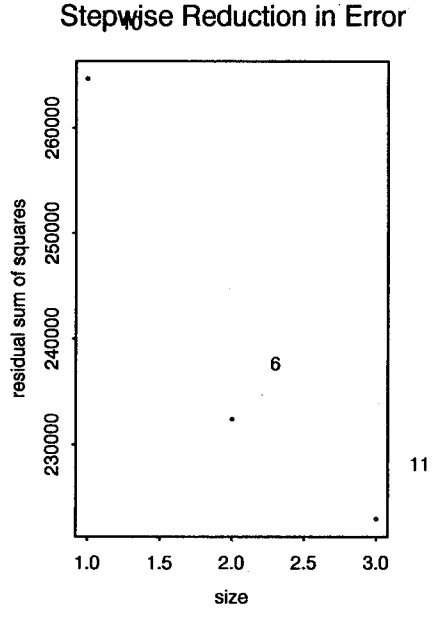
Run: FLTO_Run4

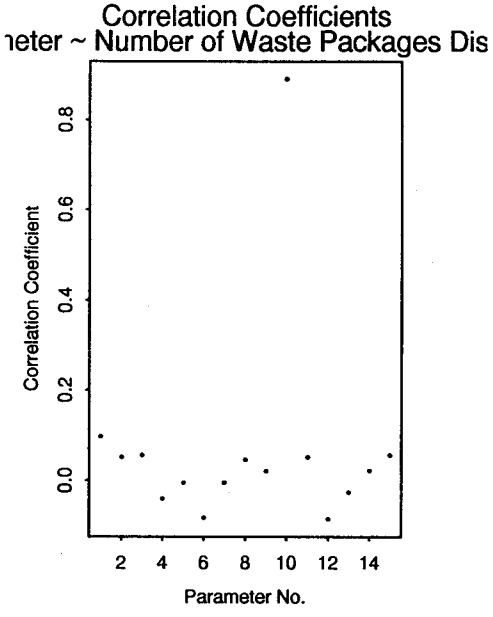
Distance to Focused Group = 5 km
Recurrence Interval = 5,000 years
Only FAULTO with Diffused Corrosion
With Backfill

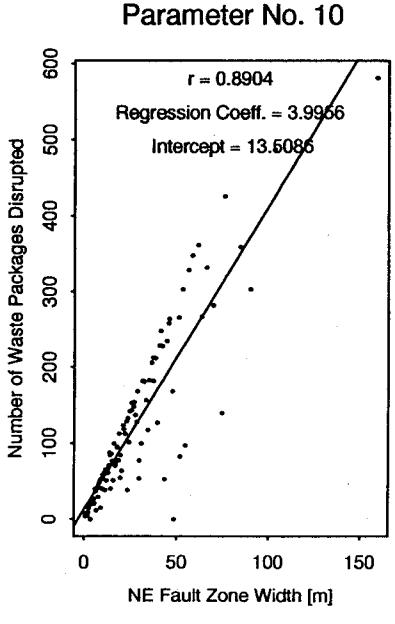
5 km Scenario
Summary Plots for Number of Waste Packages Disrupted

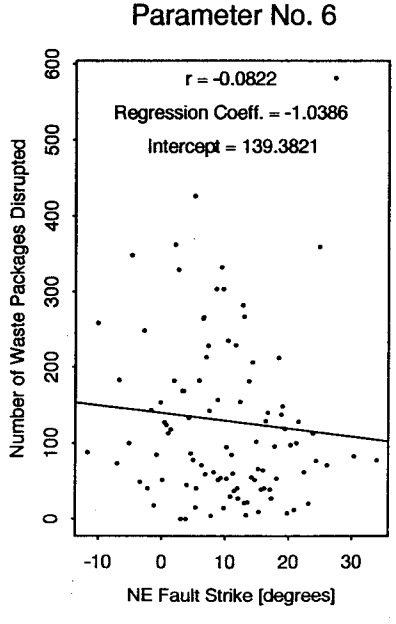


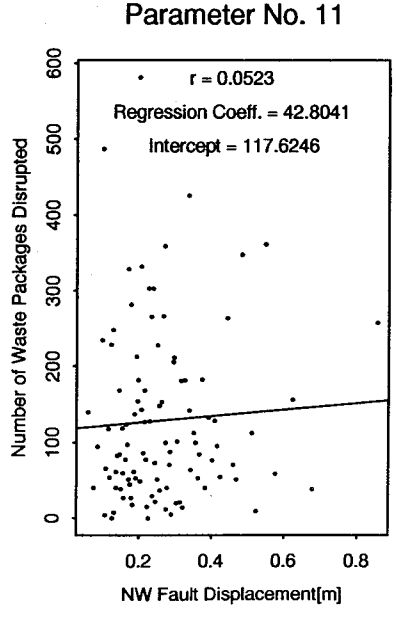


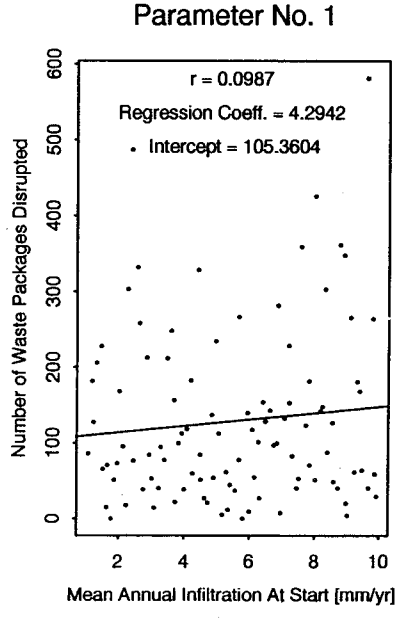












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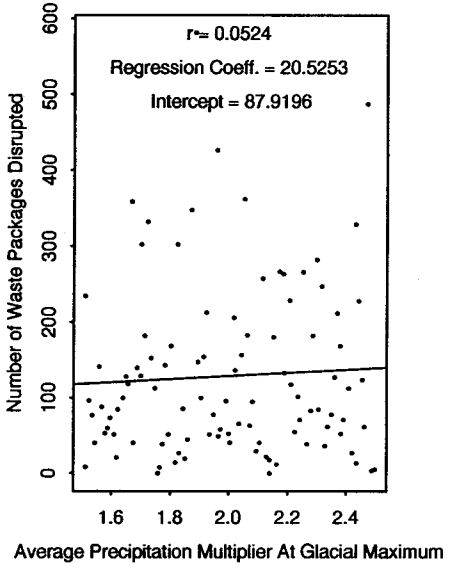

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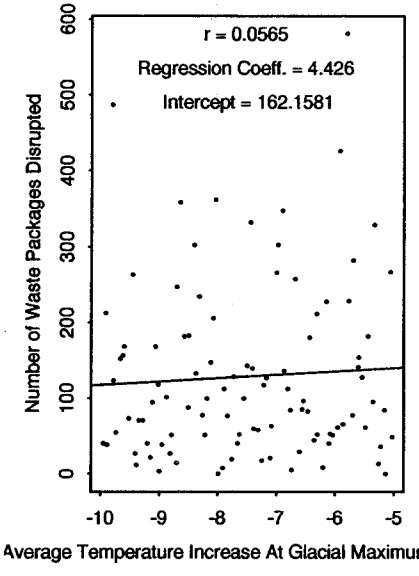

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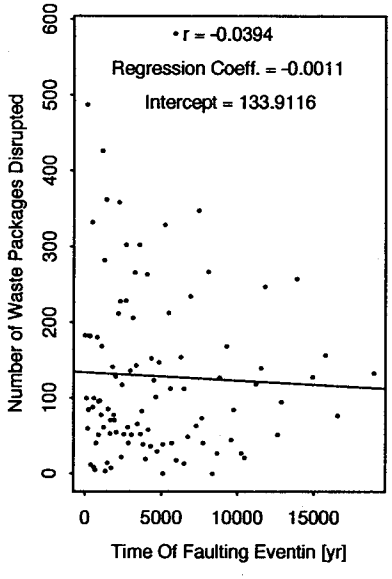

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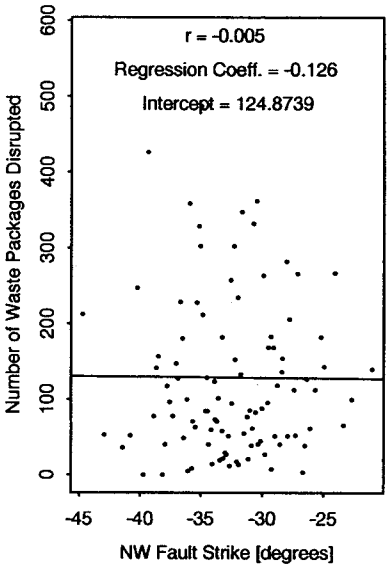

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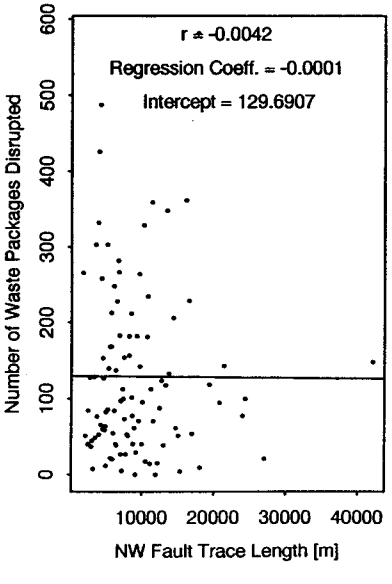

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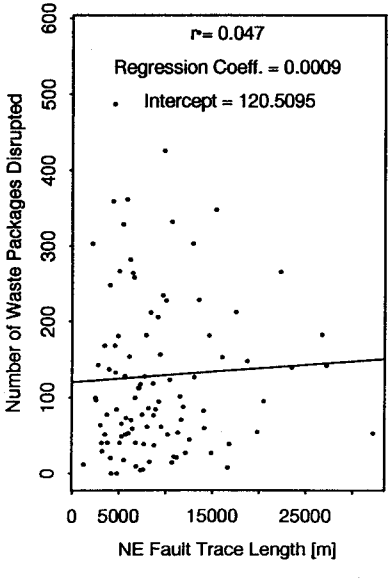

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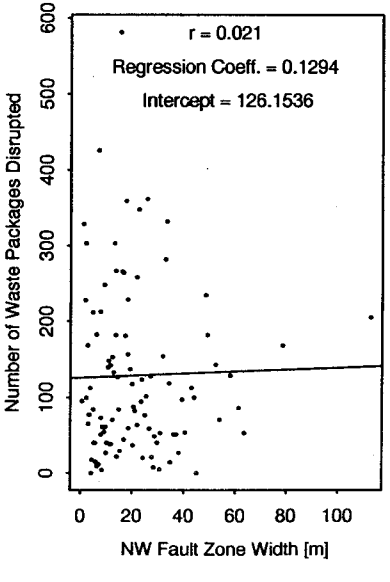
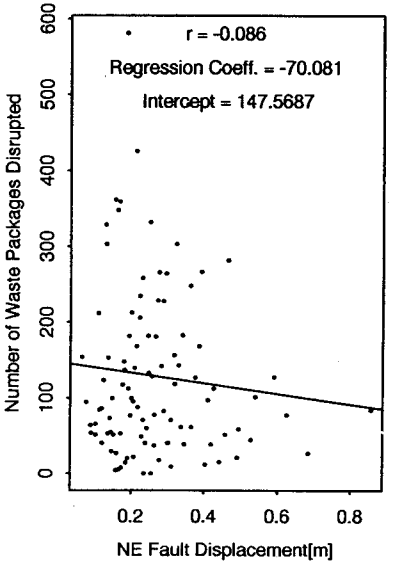
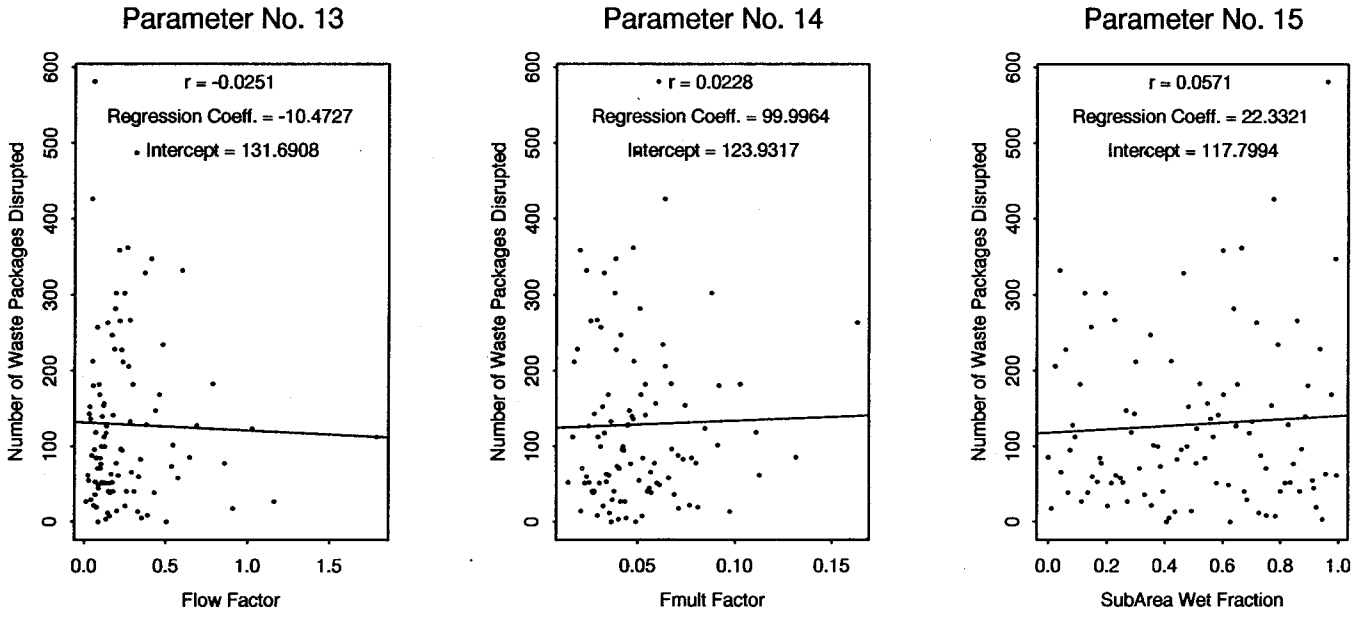
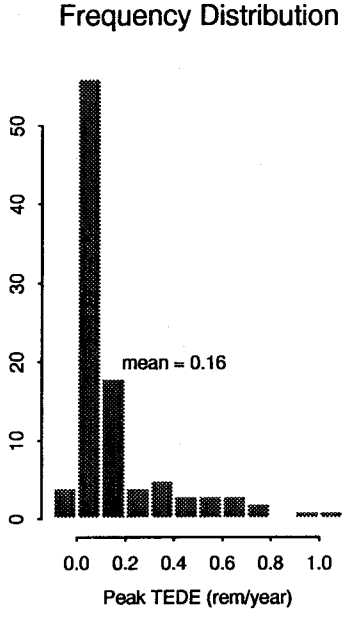


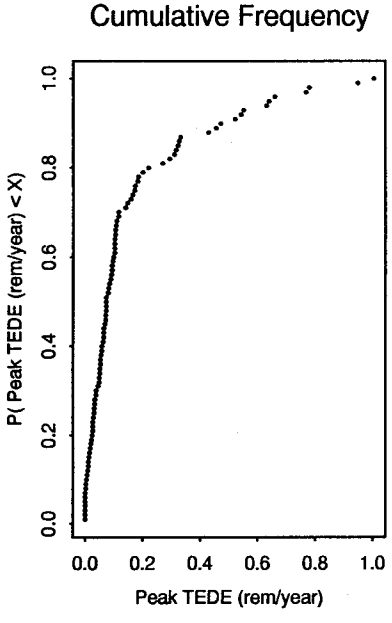
Parameter No. 12

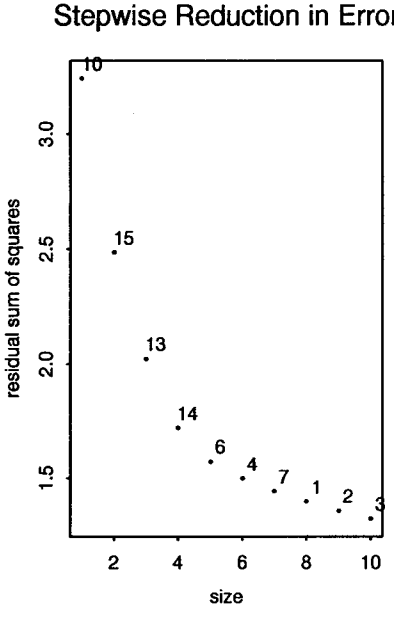


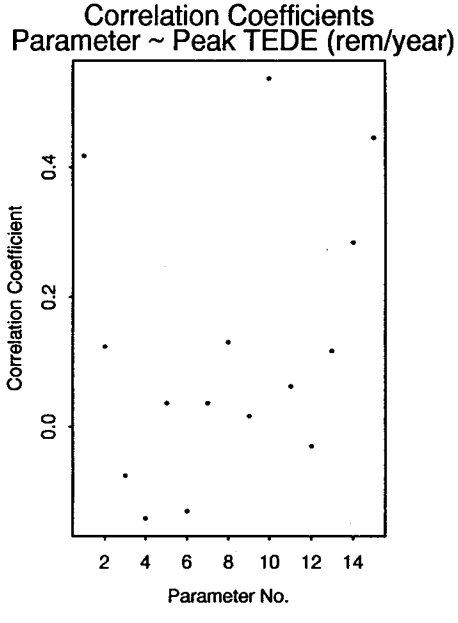

Parameter No. 13
r = -0.0251
Regression Coeff. = -10.4727
Intercept = 131.6908
Number of Waste Packages Disrupted
0
100
200
300
400
500
600
0.0
0.5
1.0
1.5
Flow Factor
Parameter No. 14
r = 0.0228
Regression Coeff. = 99.9964
Intercept = 123.9317
Number of Waste Packages Disrupted
0
100
200
300
400
500
600
0.05
0.10
0.15
Fmult Factor
Parameter No. 15
r = 0.0571
Regression Coeff. = 22.3321
Intercept = 117.7994
Number of Waste Packages Disrupted
0
100
200
300
400
500
600
0.0
0.2
0.4
0.6
0.8
1.0
SubArea Wet Fraction

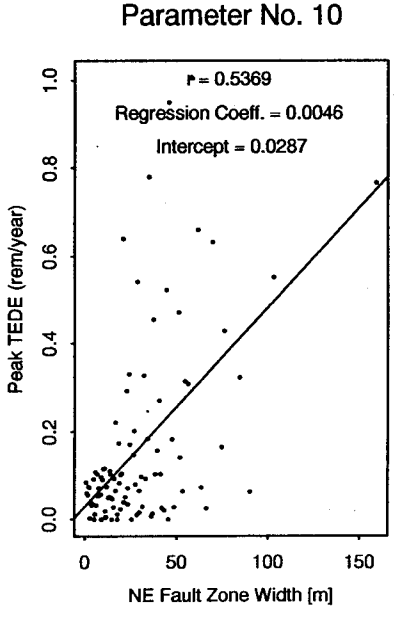
5 km Scenario
Summary Plots for Peak TEDE (rem/year)

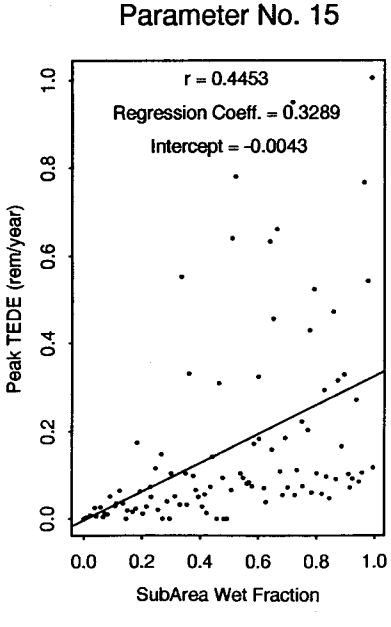


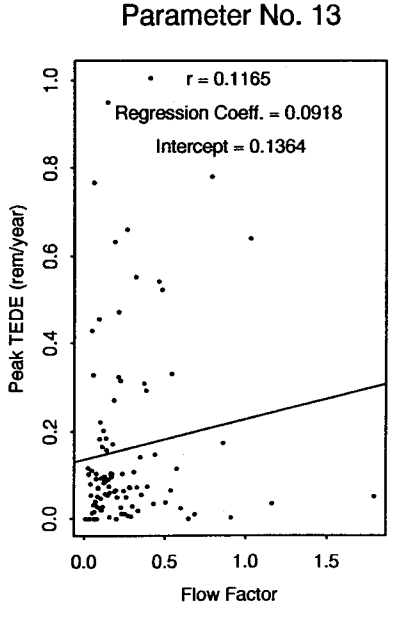


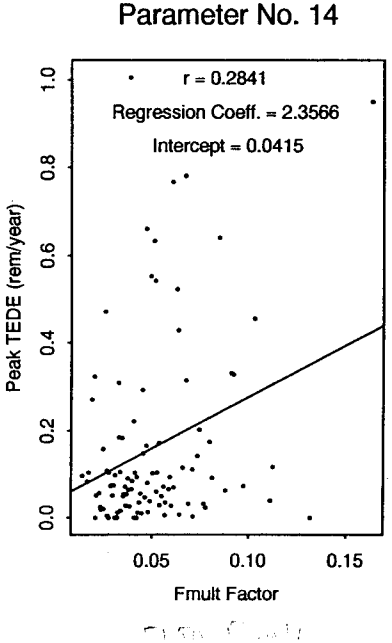






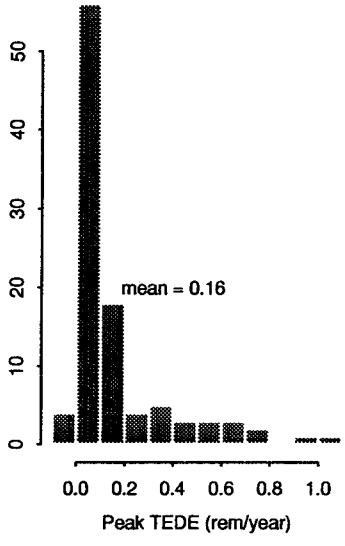




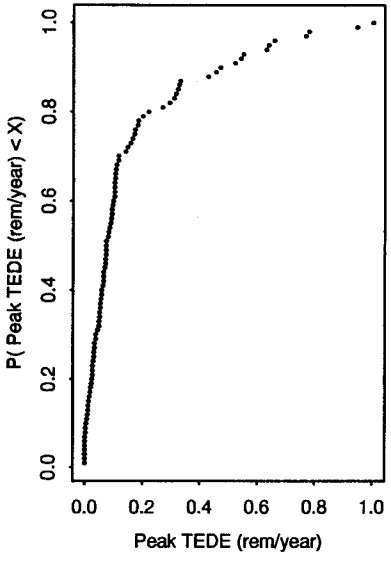


5 km Scenario
Summary Plots for Peak TEDE (rem/year)

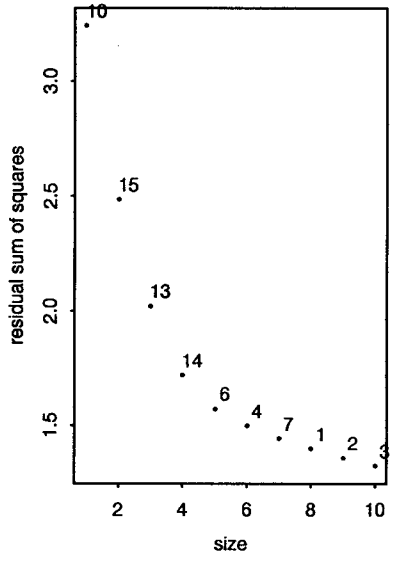
Frequency Distribution



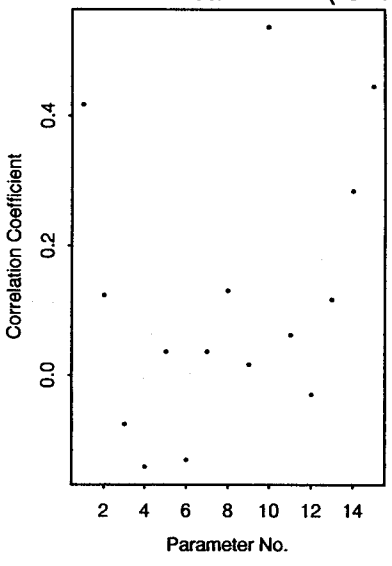
Cumulative Frequency



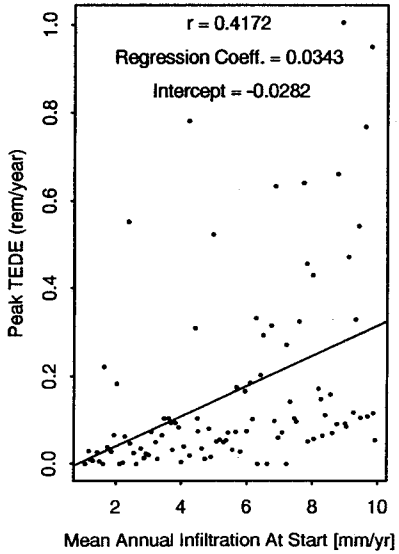
Stepwise Reduction in Error



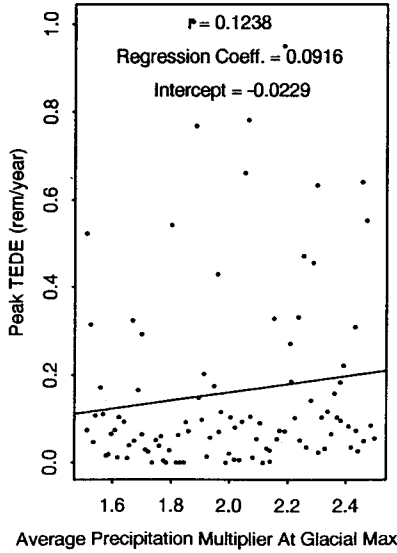
Correlation Coefficients
Parameter ~ Peak TEDE (rem/year)



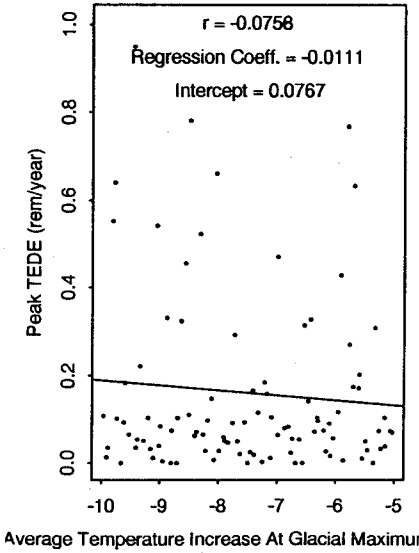
Parameter No. 1



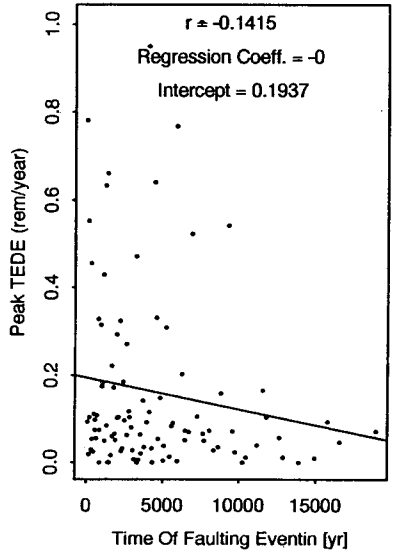
Parameter No. 2



Parameter No. 3



Parameter No. 4



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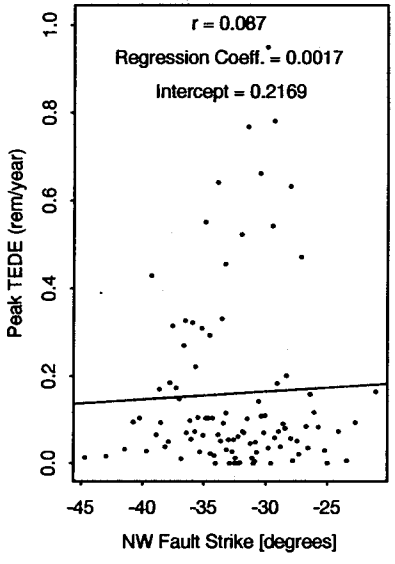

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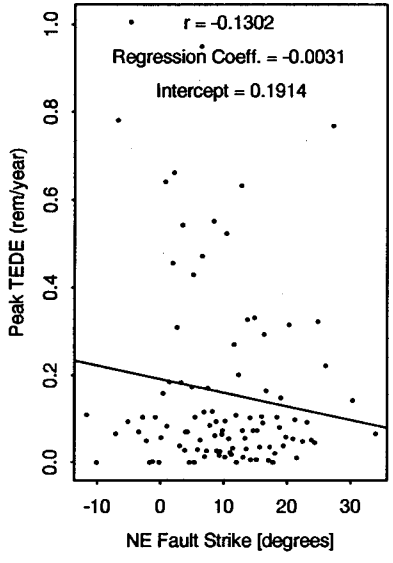

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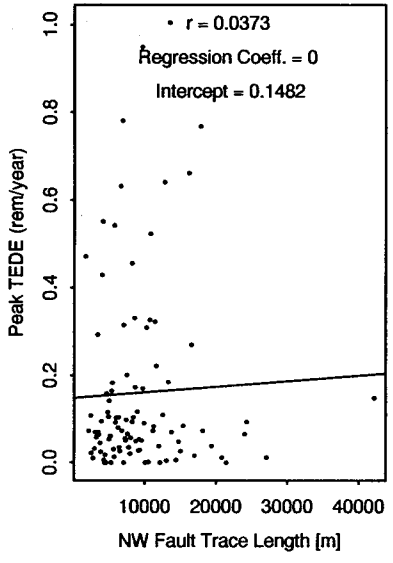

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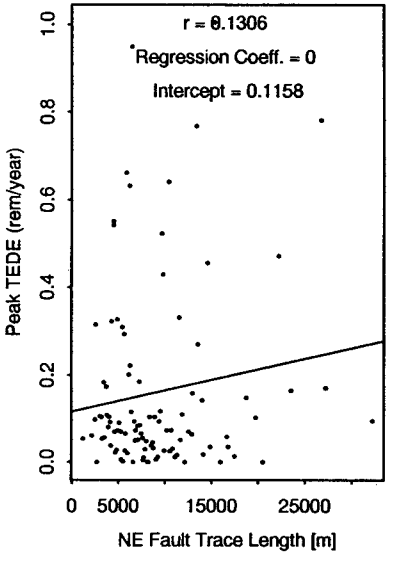
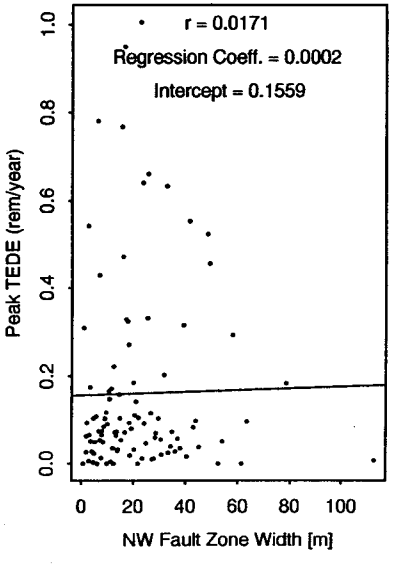


Parameter No. 9



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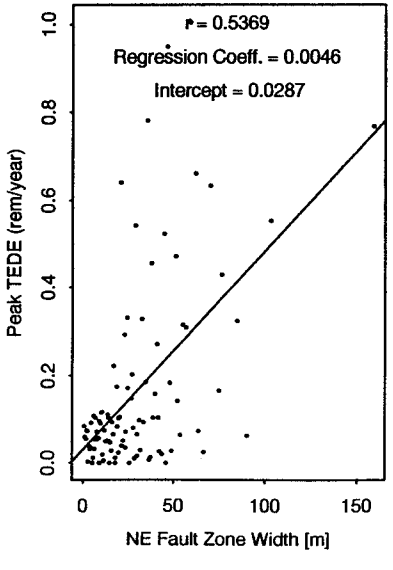

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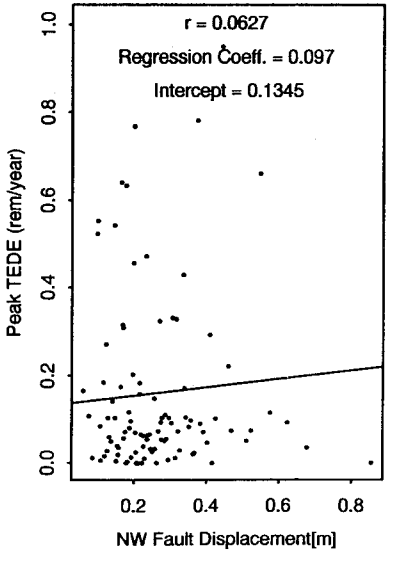

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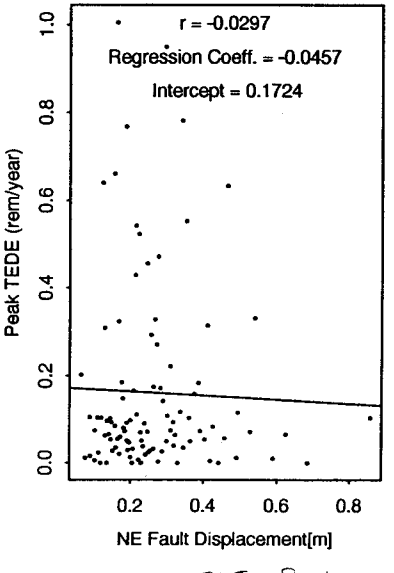
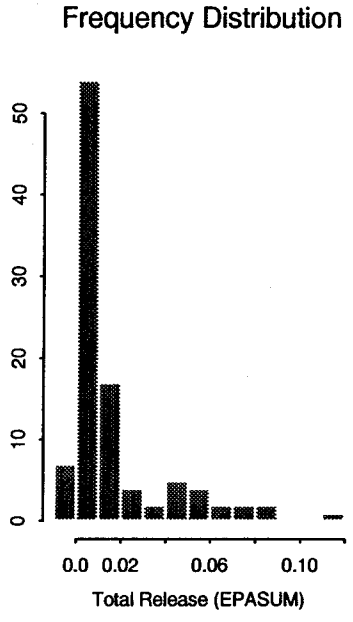
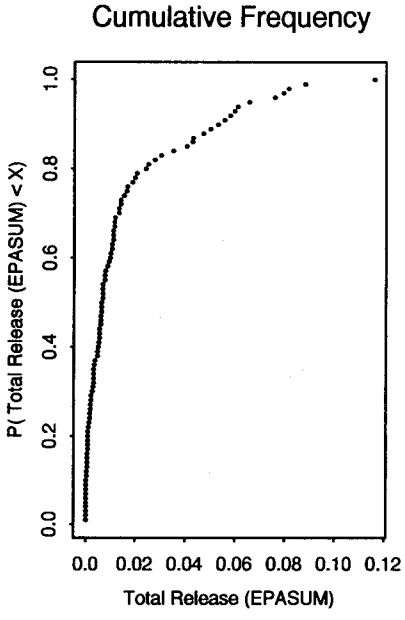
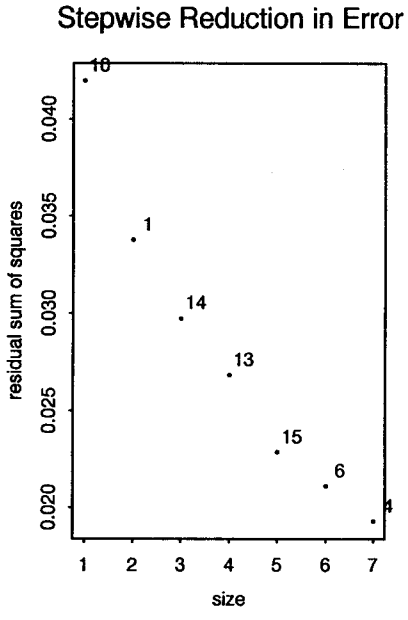


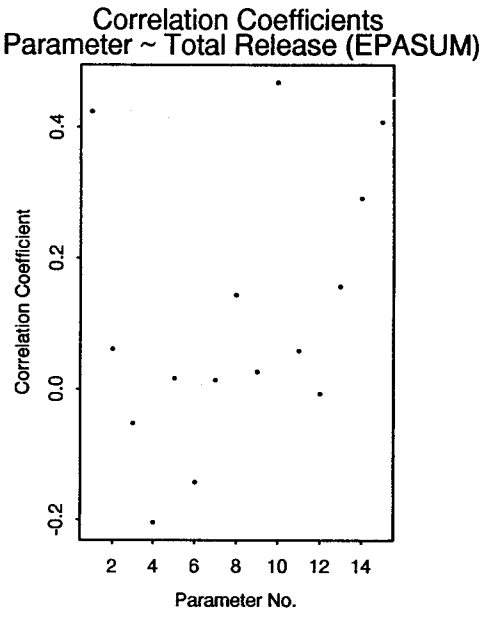
F1 To Pg 4

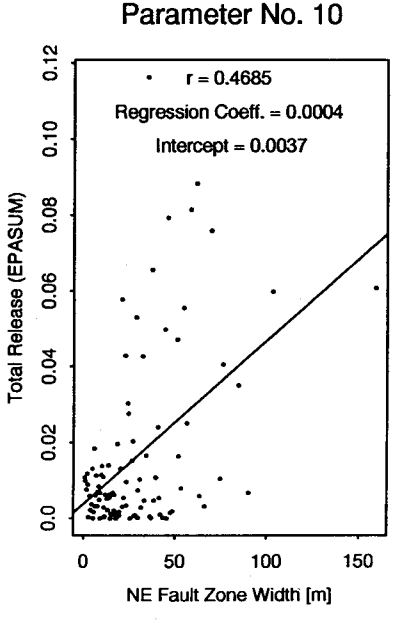
5 km Scenario
Summary Plots for Total Release (EPASUM)

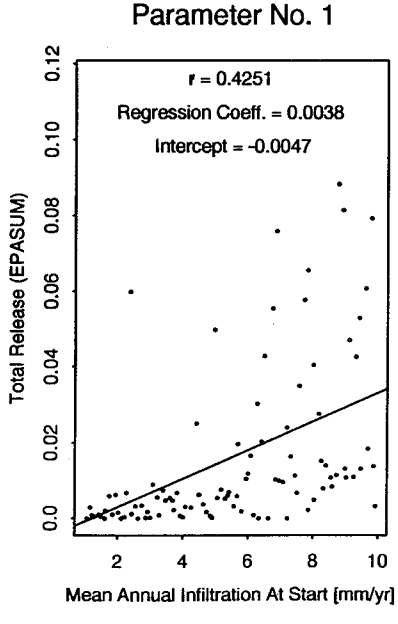


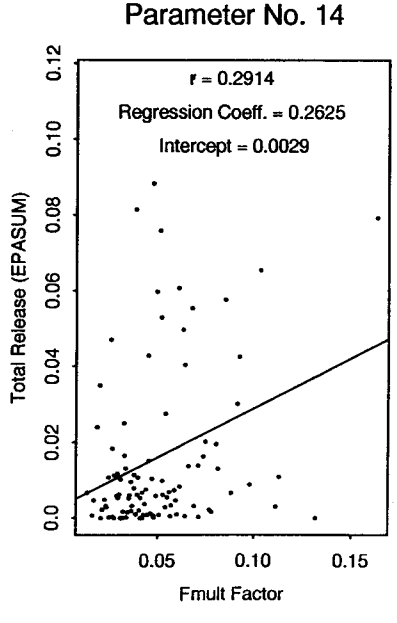


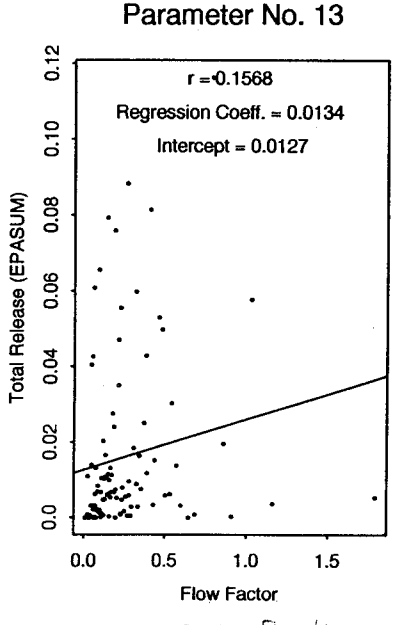




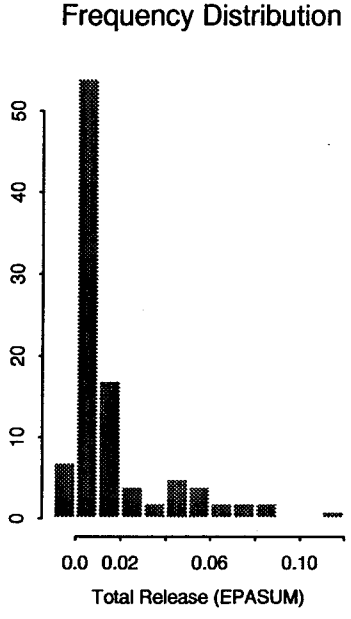


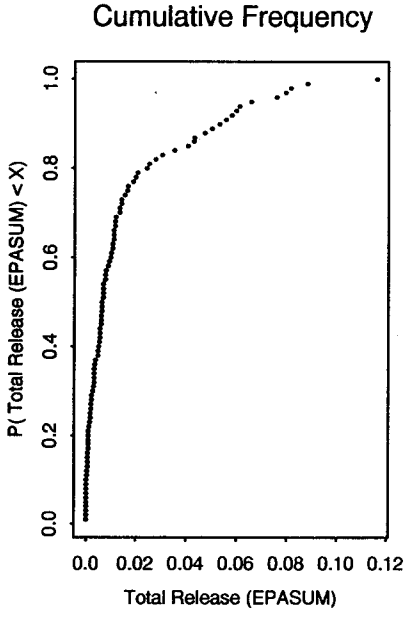


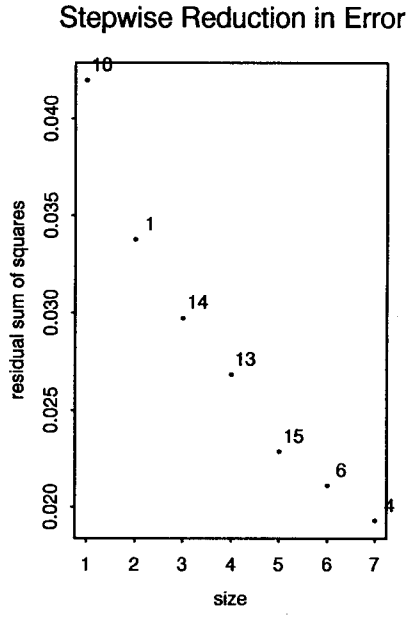


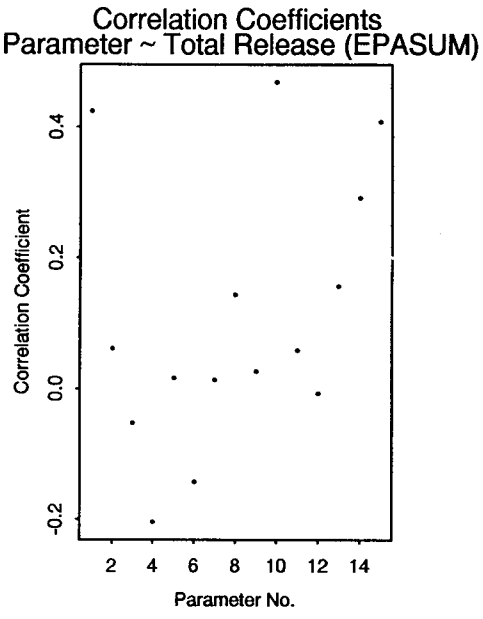


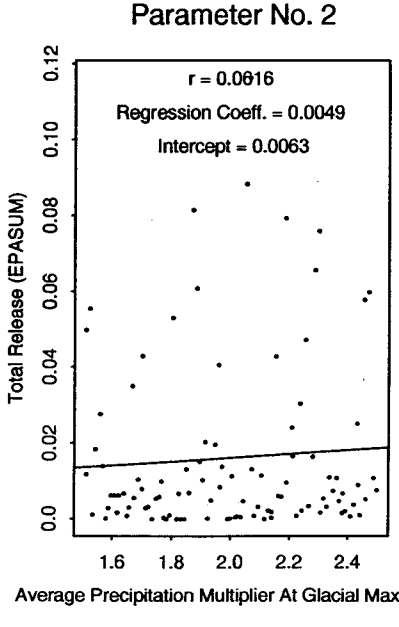
5 km Scenario
Summary Plots for Total Release (EPASUM)

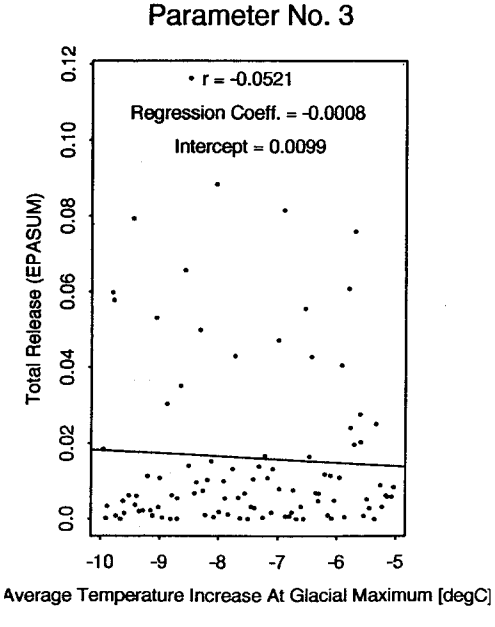


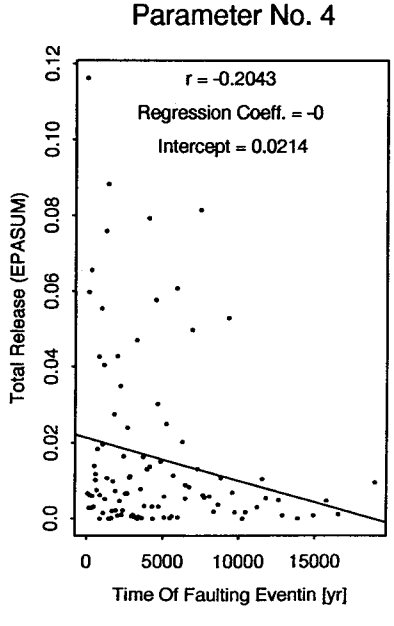


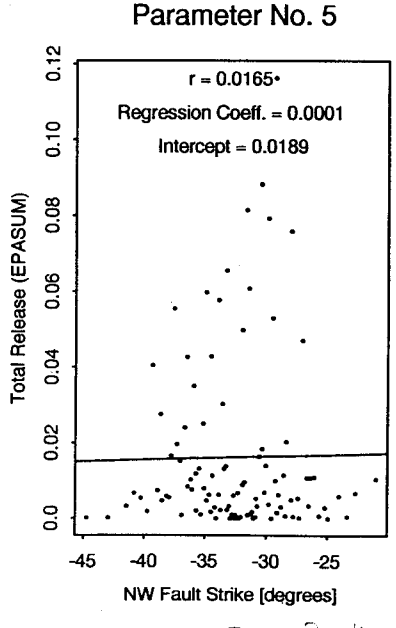




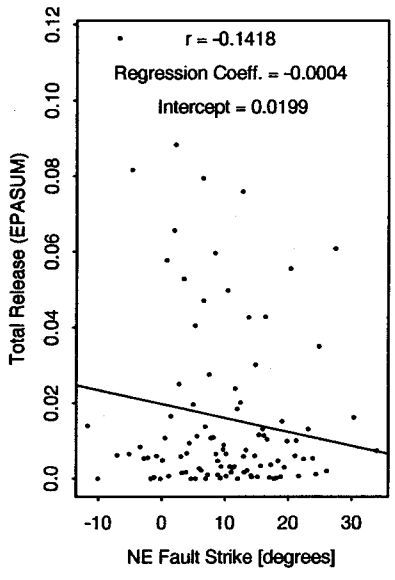




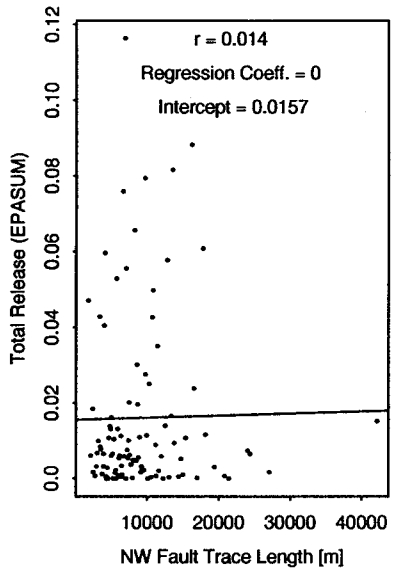




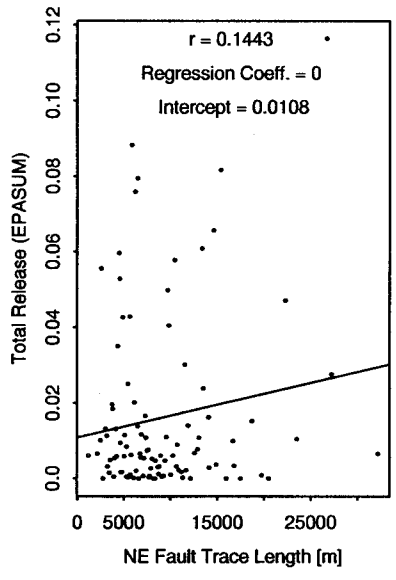
Parameter No. 6



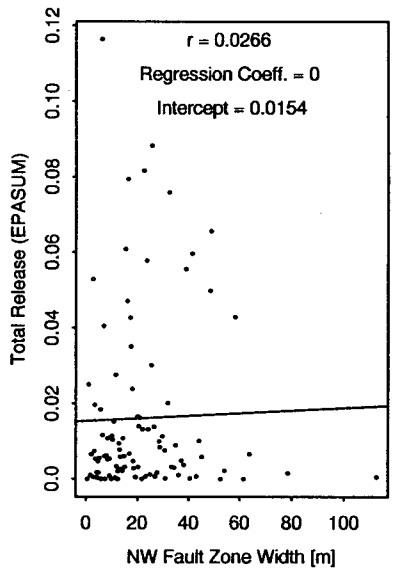
Parameter No. 7



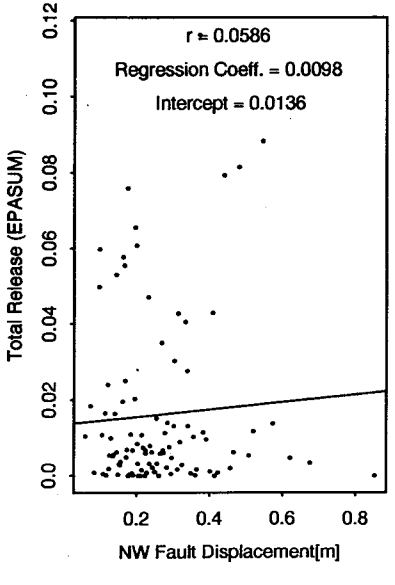
Parameter No. 8



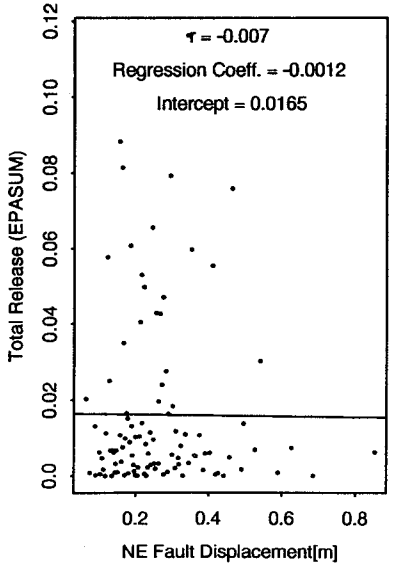
Parameter No. 9



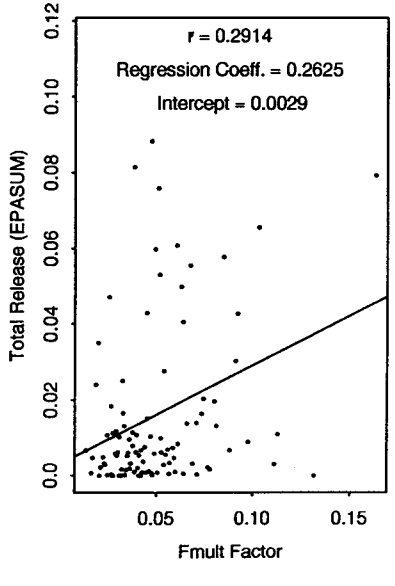
Parameter No. 11



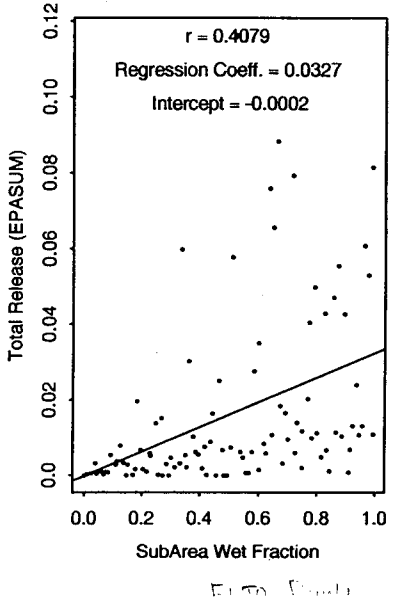
Parameter No. 12



Parameter No. 14



Parameter No. 15



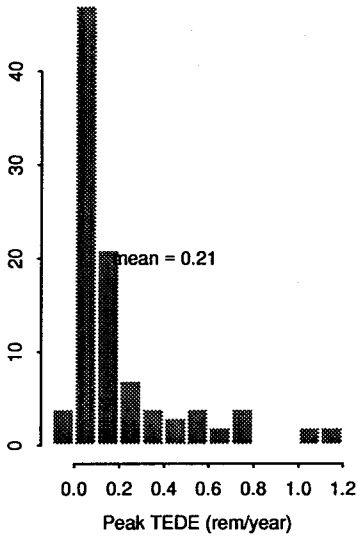
APPENDIX F:

Run: FLTO_Run5

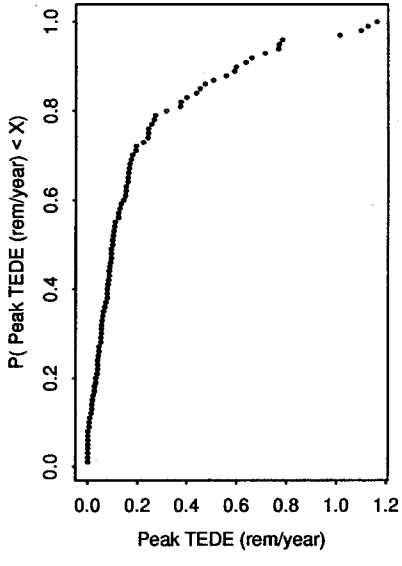
Distance to Focused Group = 5 km
Recurrence Interval = 500 years
Only FAULTO with Diffused Corrosion
With Backfill

5 km Scenario
Summary Plots for Peak TEDE (rem/year)

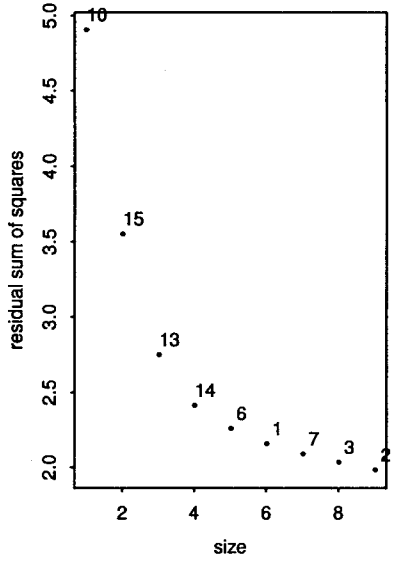
Frequency Distribution



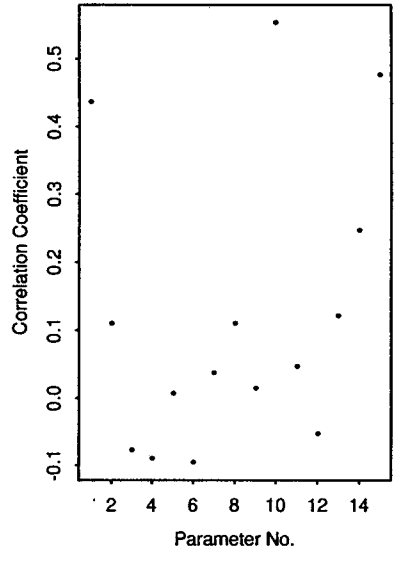
Cumulative Frequency



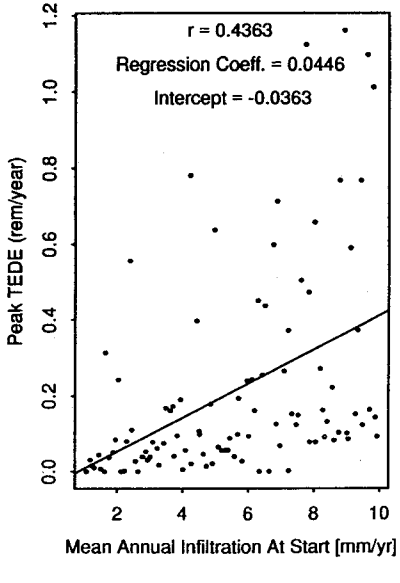
Stepwise Reduction in Error



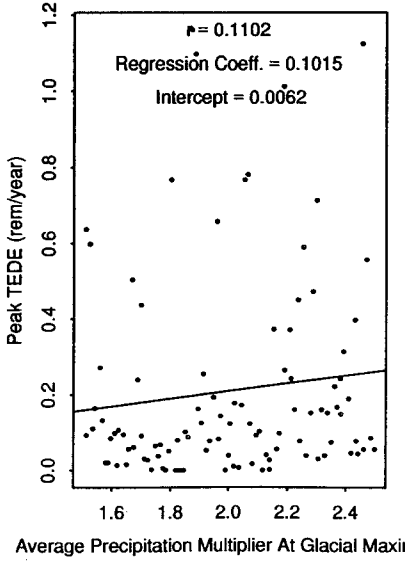
Correlation Coefficients
Parameter ~ Peak TEDE (rem/year)



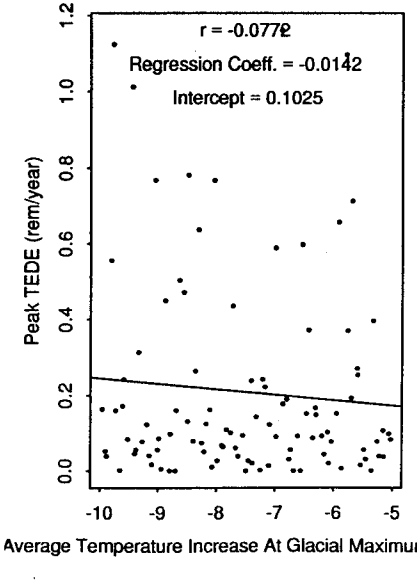
Parameter No. 1



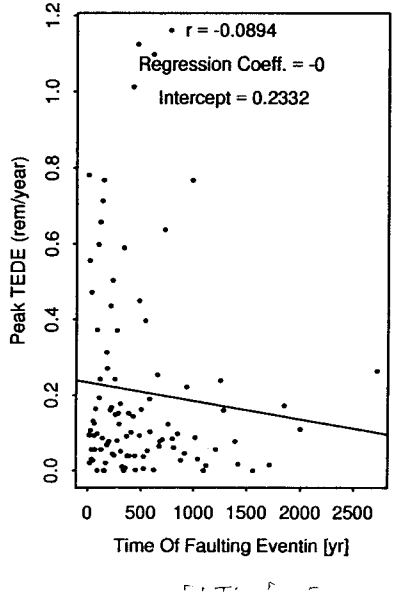
Parameter No. 2



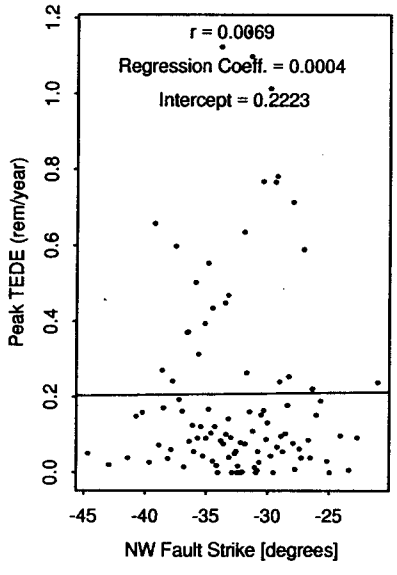
Parameter No. 3



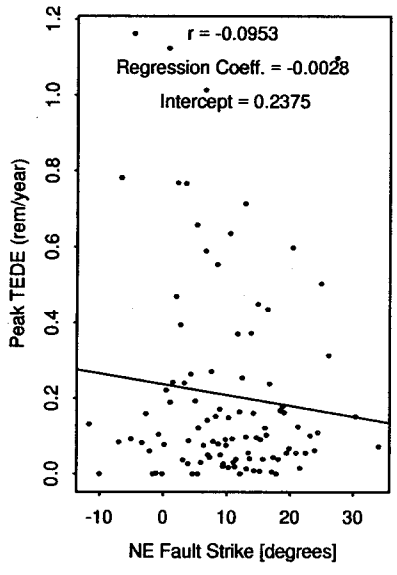
Parameter No. 4



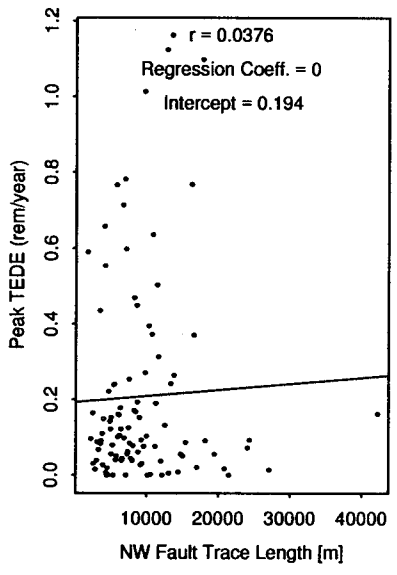
Parameter No. 5



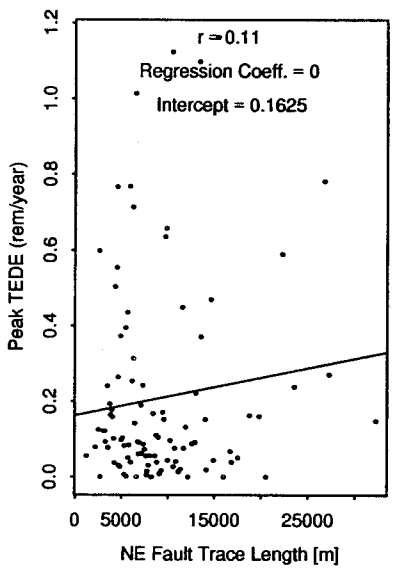
Parameter No. 6



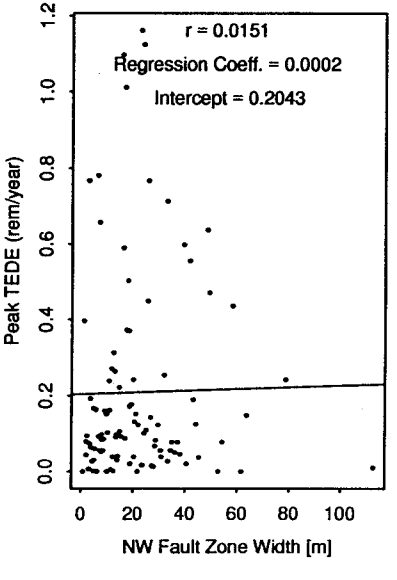
Parameter No. 7



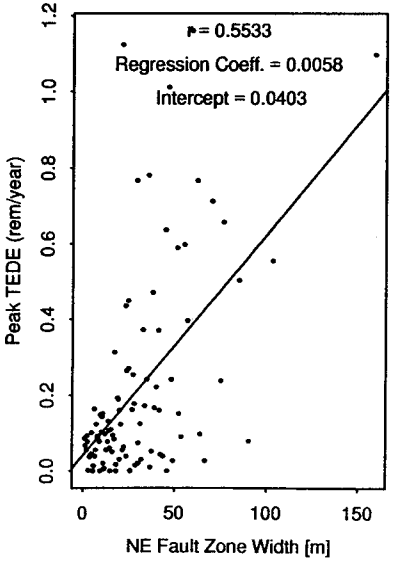
Parameter No. 8



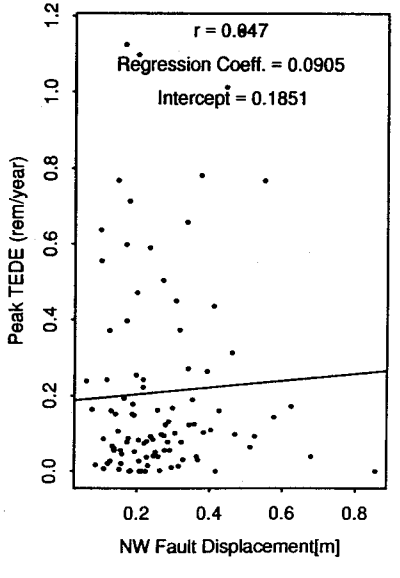
Parameter No. 9



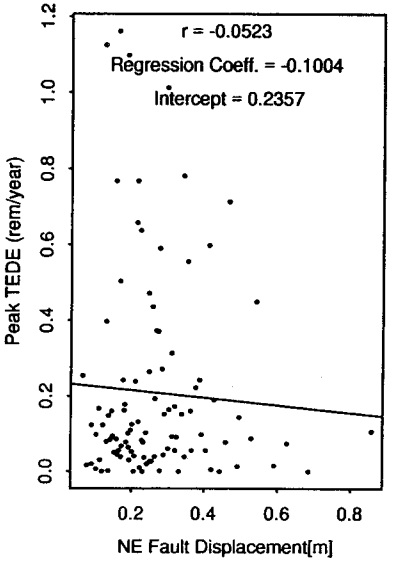
Parameter No. 10

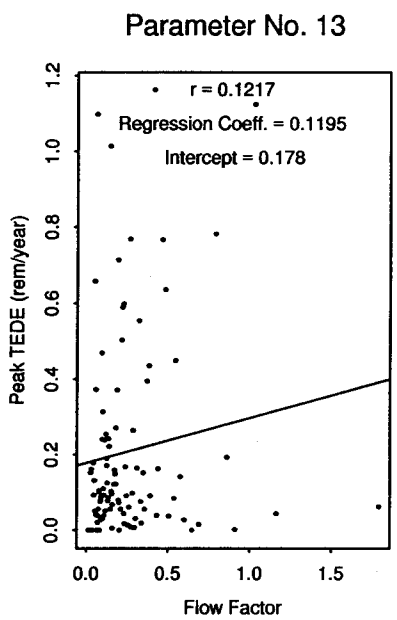


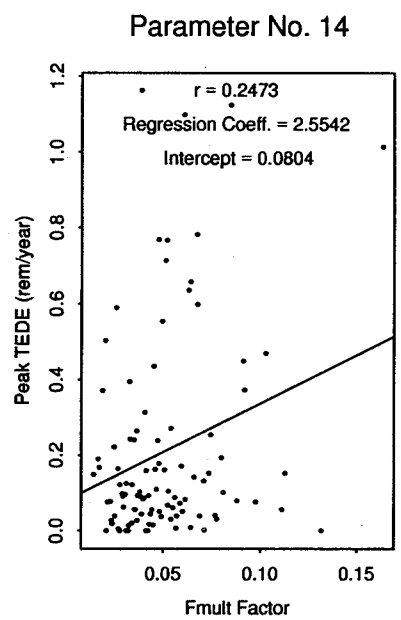
Parameter No. 11

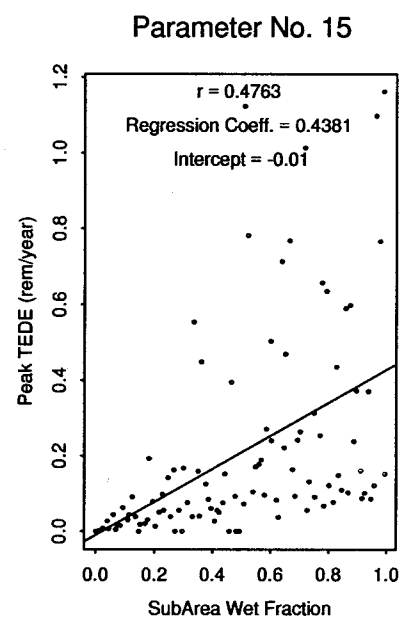


Parameter No. 12




Parameter No. 13
r = 0.1217
Regression Coeff. = 0.1195
Intercept = 0.178
Peak TEDE (rem/year)
Flow Factor
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0.0
0.5
1.0
1.5

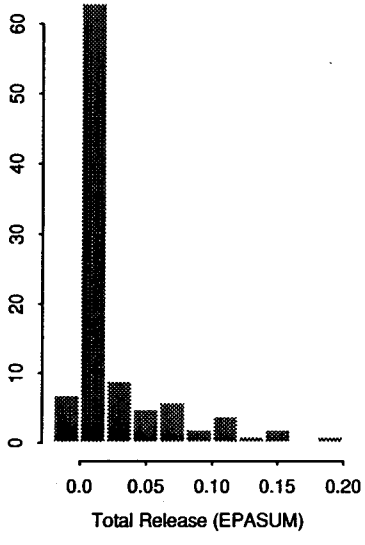

Parameter No. 14
r = 0.2473
Regression Coeff. = 2.5542
Intercept = 0.0804
Peak TEDE (rem/year)
Fmult Factor
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0.05
0.10
0.15


Parameter No. 15
r = 0.4763
Regression Coeff. = 0.4381
Intercept = -0.01
Peak TEDE (rem/year)
SubArea Wet Fraction
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0.0
0.2
0.4
0.6
0.8
1.0

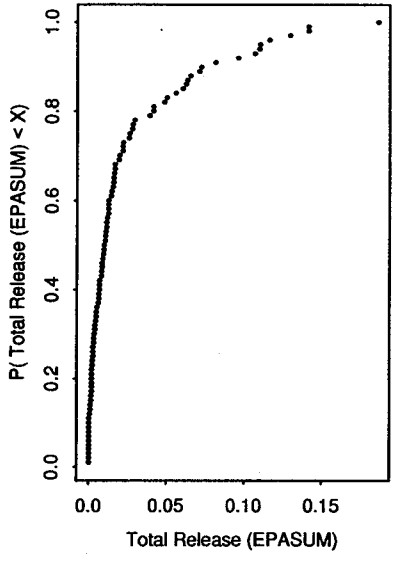
FLTA Rule

5 km Scenario
Summary Plots for Total Release (EPASUM)

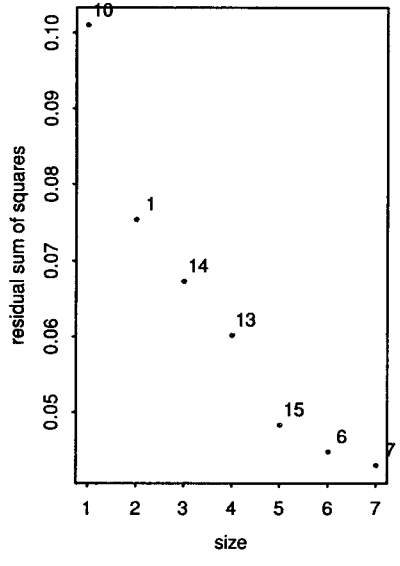
Frequency Distribution



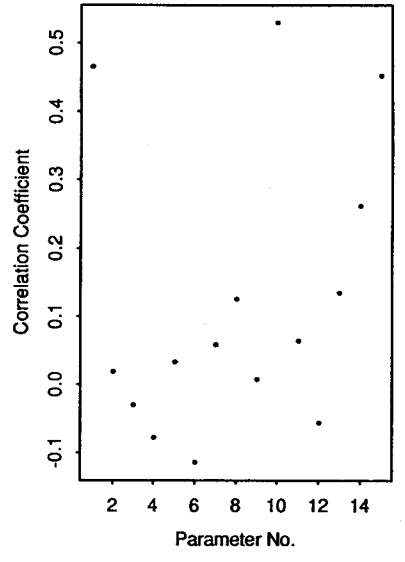
Cumulative Frequency



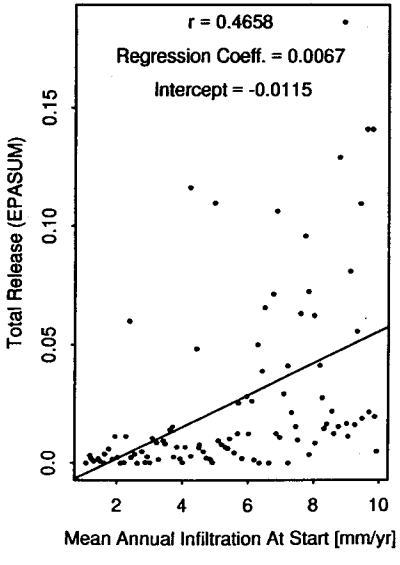
Stepwise Reduction in Error



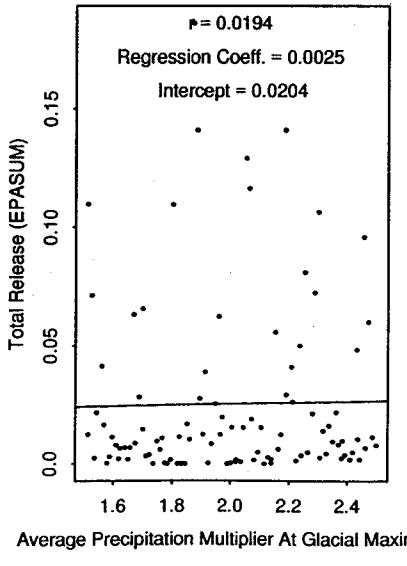
Correlation Coefficients
Parameter ~ Total Release (EPASUM)



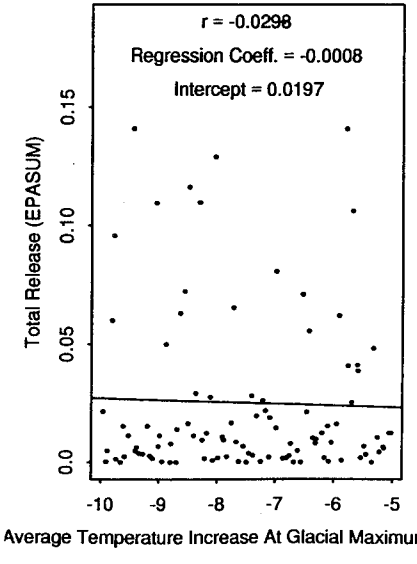
Parameter No. 1



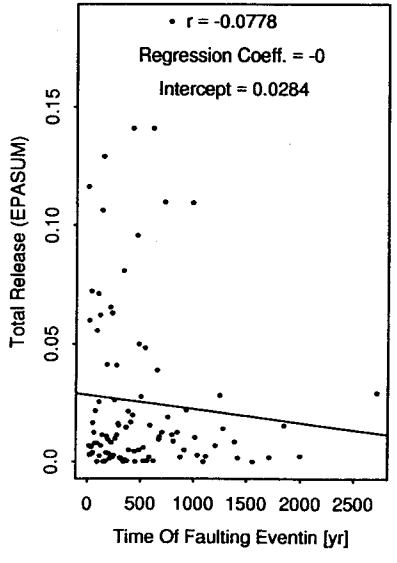
Parameter No. 2



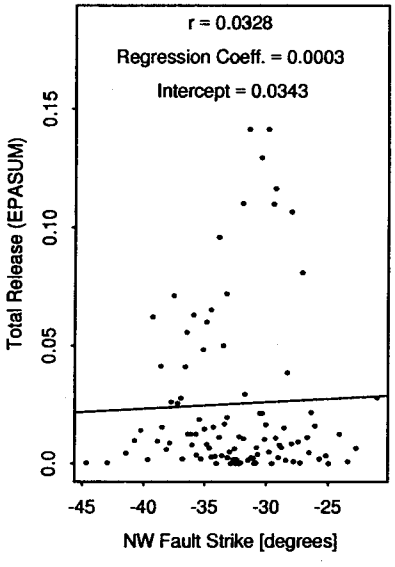
Parameter No. 3



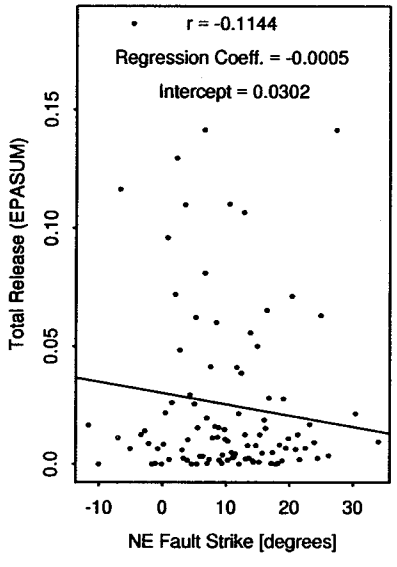
Parameter No. 4



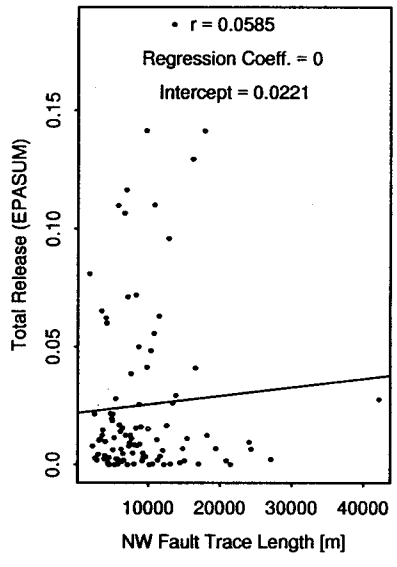
Parameter No. 5



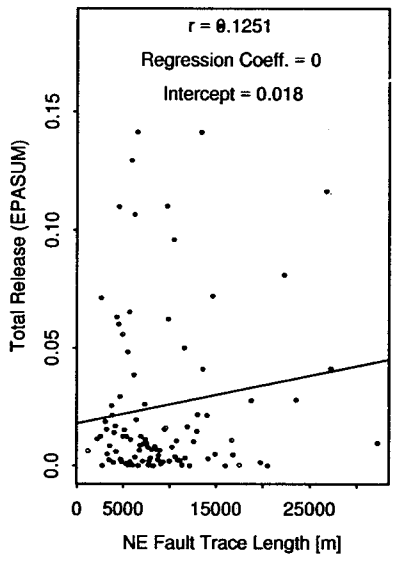
Parameter No. 6



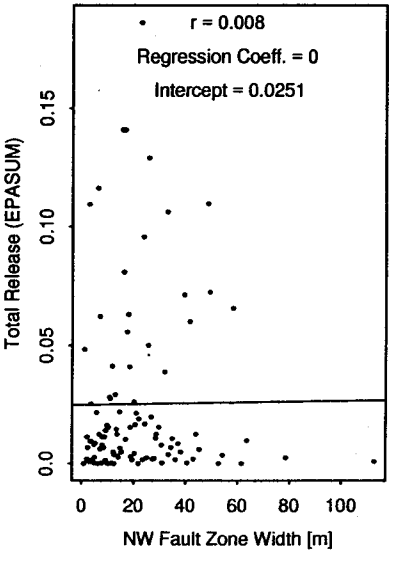
Parameter No. 7



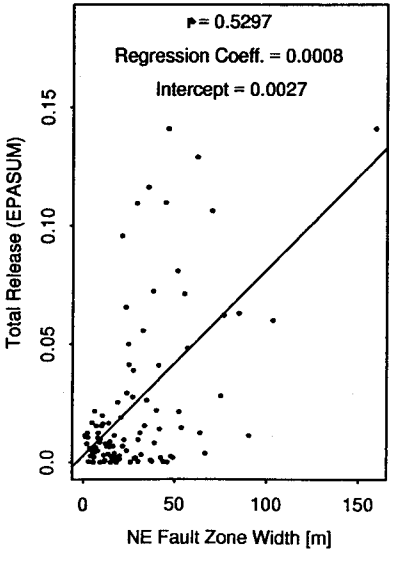
Parameter No. 8



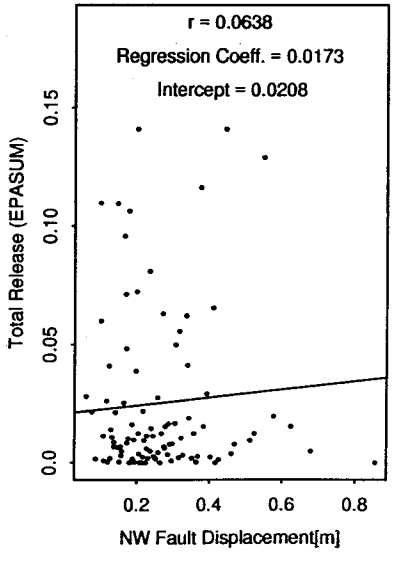
Parameter No. 9



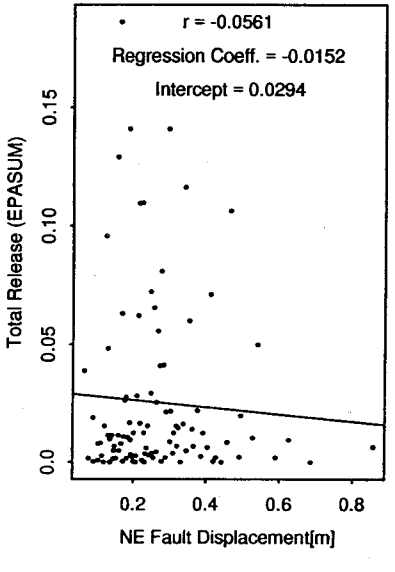
Parameter No. 10



Parameter No. 11

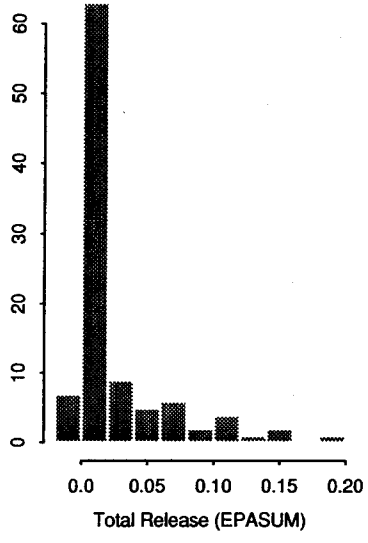


Parameter No. 12

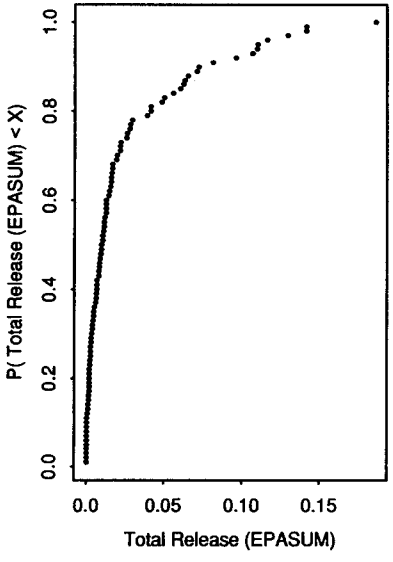


5 km Scenario
Summary Plots for Total Release (EPASUM)

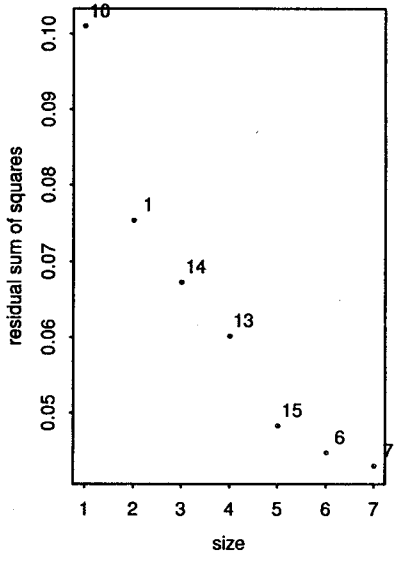
Frequency Distribution



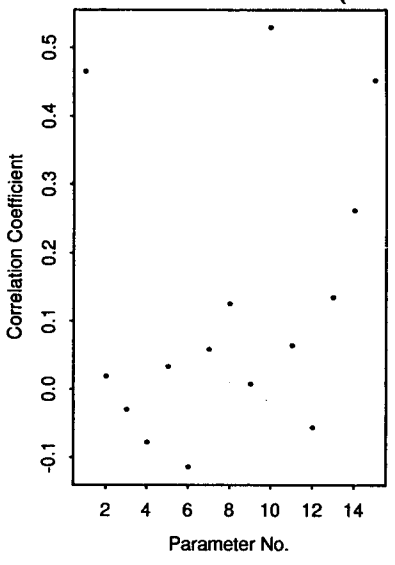
Cumulative Frequency



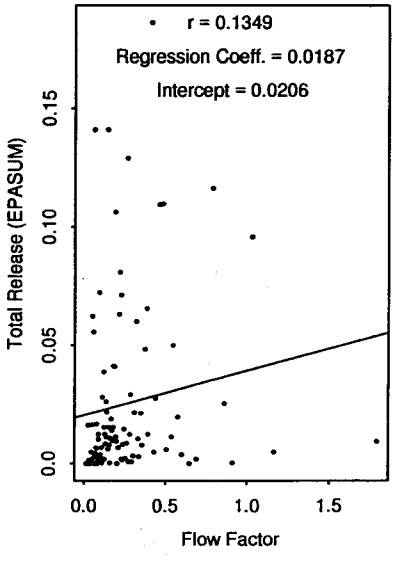
Stepwise Reduction in Error



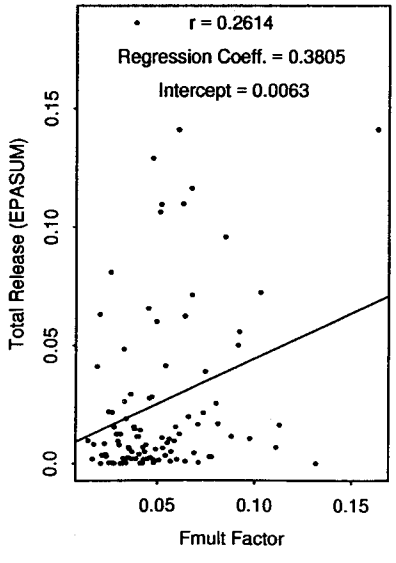
Correlation Coefficients
Parameter ~ Total Release (EPASUM)



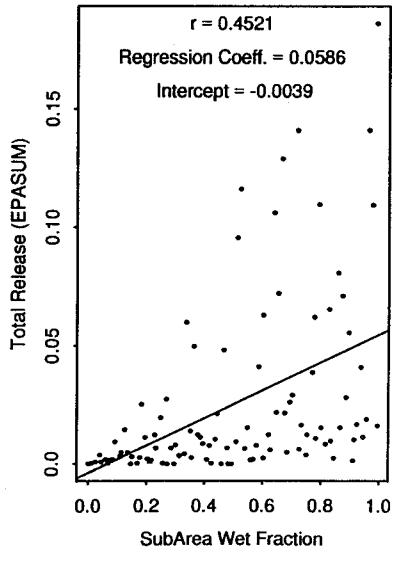
Parameter No. 13



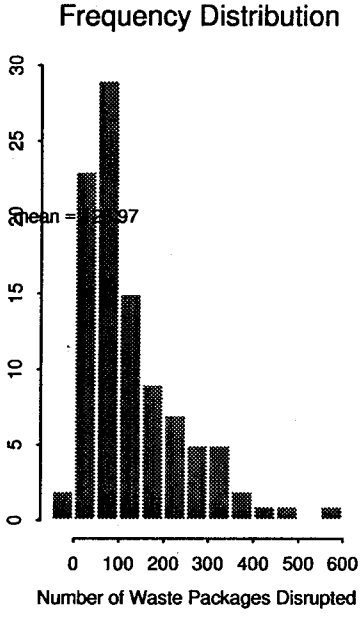
Parameter No. 14

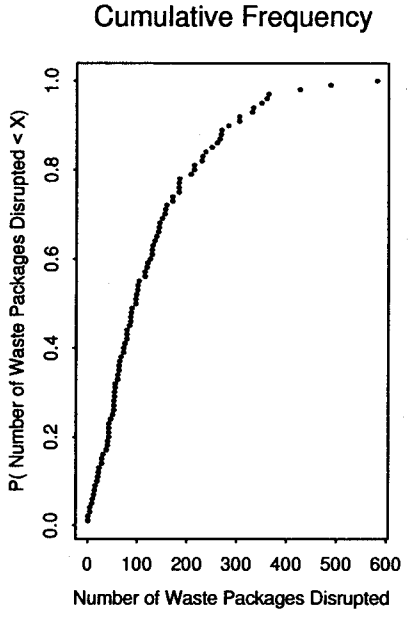


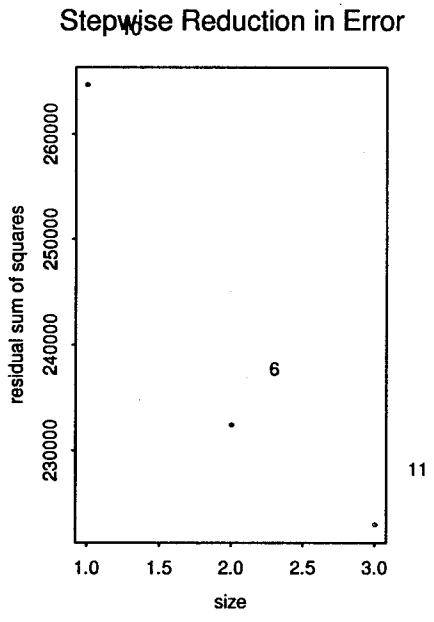
Parameter No. 15

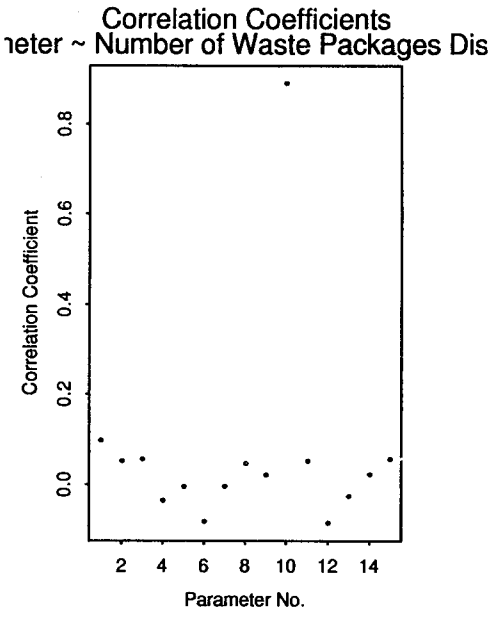


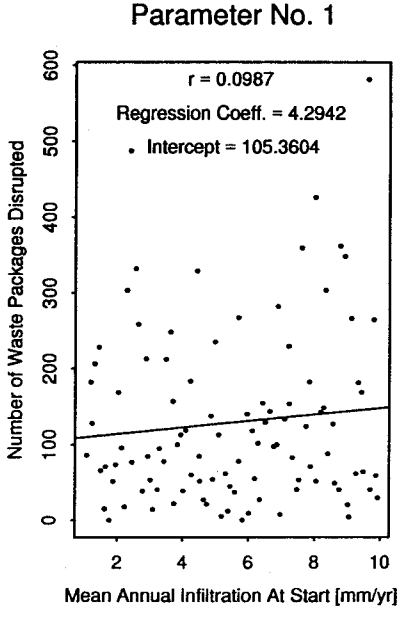
5 km Scenario
Summary Plots for Number of Waste Packages Disrupted

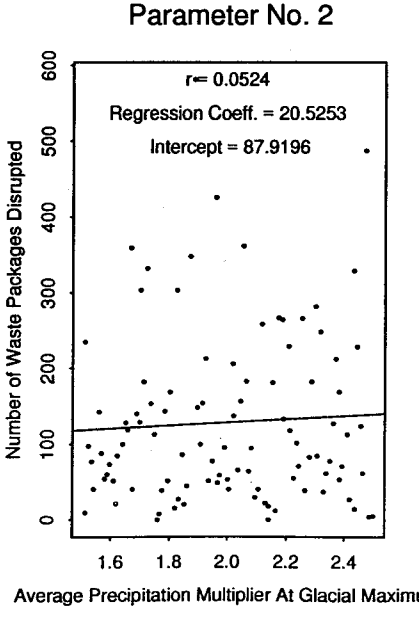


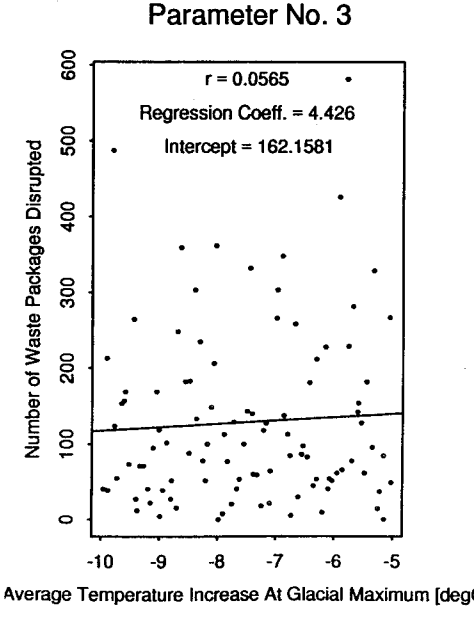


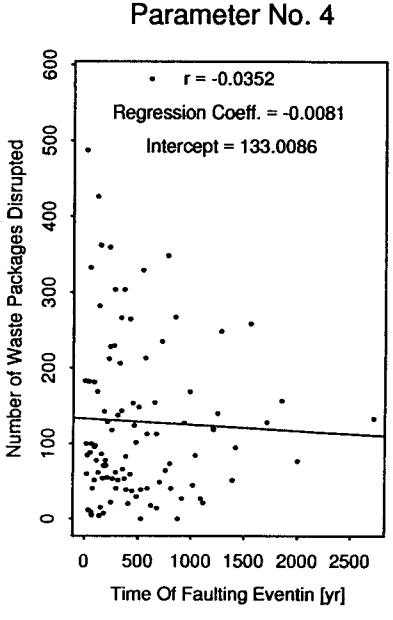


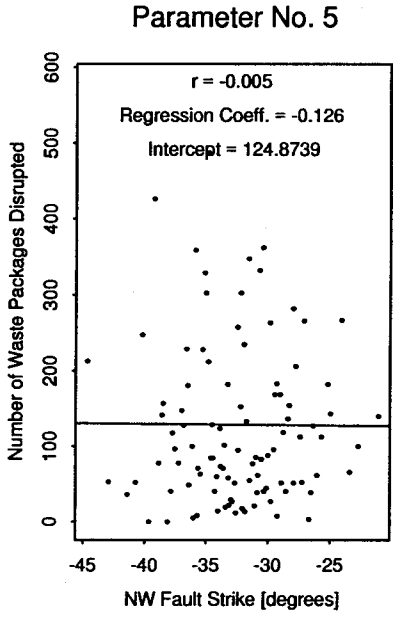


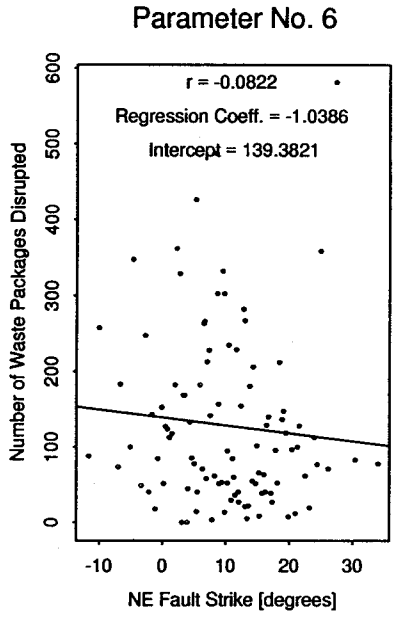


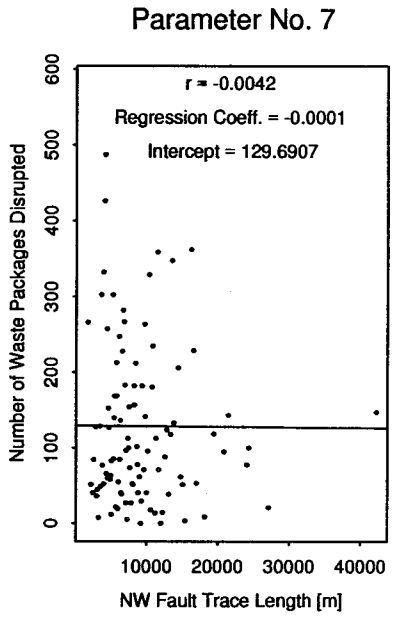


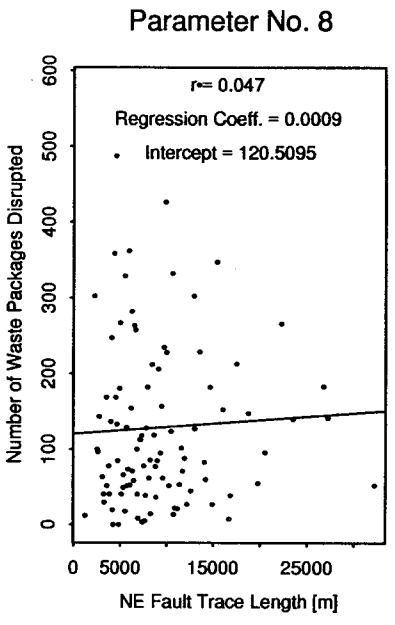


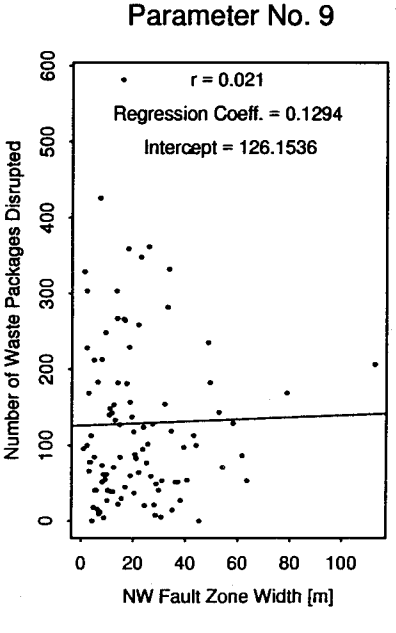


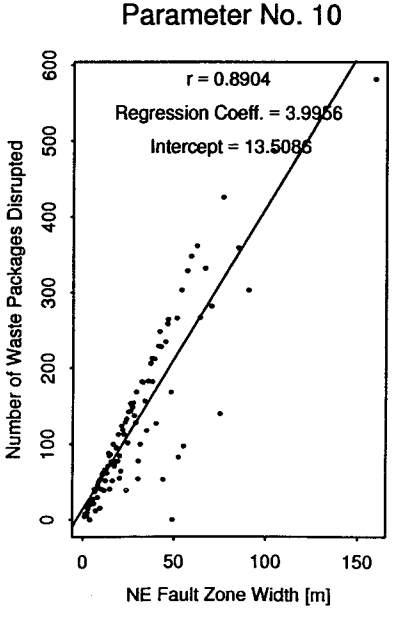

Parameter No. 5
r = -0.005
Regression Coeff. = -0.126
Intercept = 124.8739
Number of Waste Packages Disrupted
0
100
200
300
400
500
600
-45
-40
-35
-30
-25
NW Fault Strike [degrees]

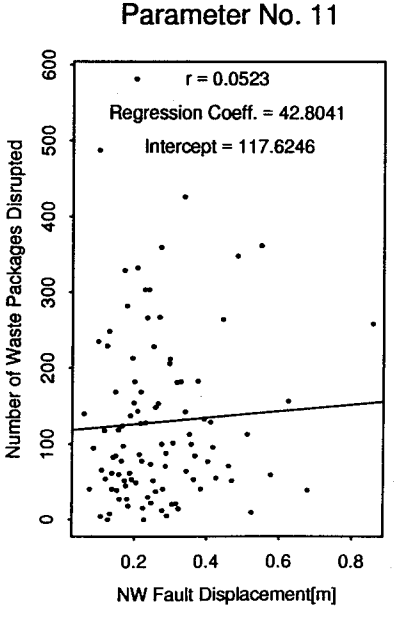

Parameter No. 6
r = -0.0822
Regression Coeff. = -1.0386
Intercept = 139.3821
Number of Waste Packages Disrupted
0
100
200
300
400
500
600
-10
0
10
20
30
NE Fault Strike [degrees]

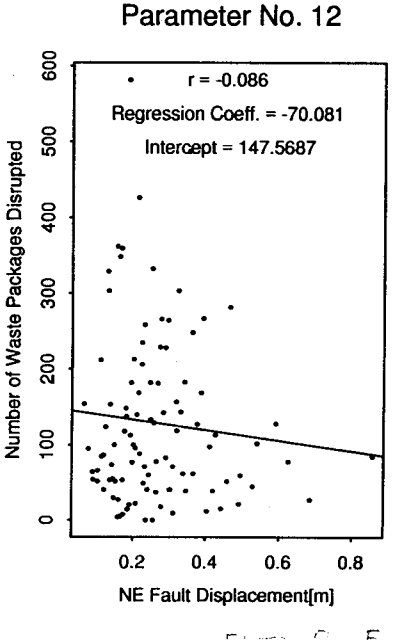

Parameter No. 7
r = -0.0042
Regression Coeff. = -0.0001
Intercept = 129.6907
Number of Waste Packages Disrupted
0
100
200
300
400
500
600
10000
20000
30000
40000
NW Fault Trace Length [m]

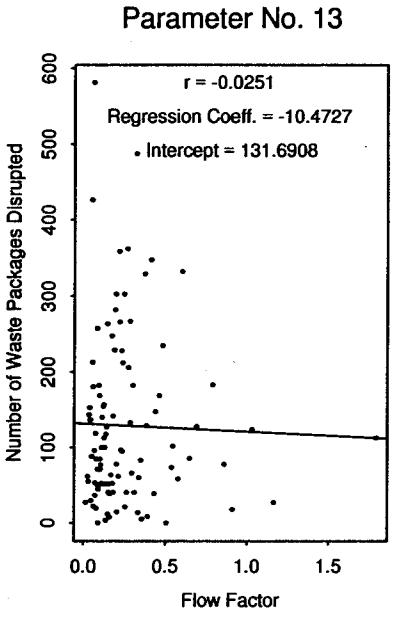

Parameter No. 8
r = 0.047
Regression Coeff. = 0.0009
Intercept = 120.5095
Number of Waste Packages Disrupted
0
100
200
300
400
500
600
0
5000
15000
25000
NE Fault Trace Length [m]

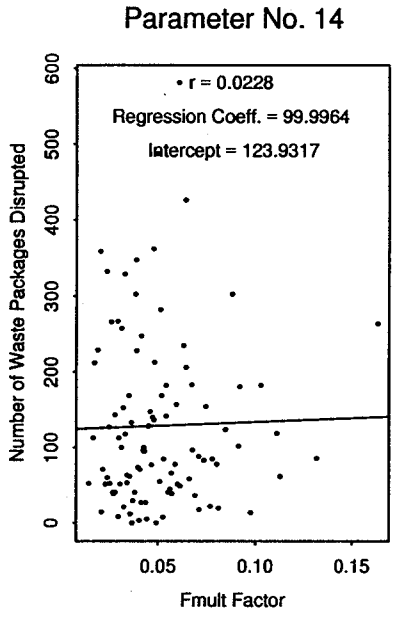

Parameter No. 9
r = 0.021
Regression Coeff. = 0.1294
Intercept = 126.1536
Number of Waste Packages Disrupted
0
100
200
300
400
500
600
0
20
40
60
80
100
NW Fault Zone Width [m]

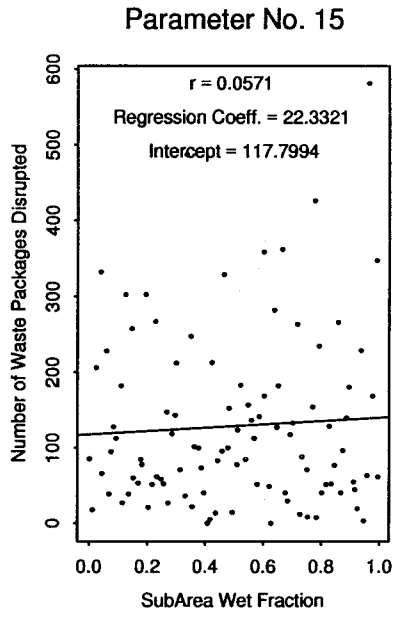

Parameter No. 10
r = 0.8904
Regression Coeff. = 3.9956
Intercept = 13.5086
Number of Waste Packages Disrupted
0
100
200
300
400
500
600
0
50
100
150
NE Fault Zone Width [m]


Parameter No. 11
r = 0.0523
Regression Coeff. = 42.8041
Intercept = 117.6246
Number of Waste Packages Disrupted
0
100
200
300
400
500
600
0.2
0.4
0.6
0.8
NW Fault Displacement[m]


Parameter No. 12
r = -0.086
Regression Coeff. = -70.081
Intercept = 147.5687
Number of Waste Packages Disrupted
0
100
200
300
400
500
600
0.2
0.4
0.6
0.8
NE Fault Displacement[m]


Parameter No. 13
r = -0.0251
Regression Coeff. = -10.4727
Intercept = 131.6908
Number of Waste Packages Disrupted
0
100
200
300
400
500
600
0.0
0.5
1.0
1.5
Flow Factor


Parameter No. 14
r = 0.0228
Regression Coeff. = 99.9964
Intercept = 123.9317
Number of Waste Packages Disrupted
0
100
200
300
400
500
600
0.05
0.10
0.15
Fmult Factor


Parameter No. 15
r = 0.0571
Regression Coeff. = 22.3321
Intercept = 117.7994
Number of Waste Packages Disrupted
0
100
200
300
400
500
600
0.0
0.2
0.4
0.6
0.8
1.0
SubArea Wet Fraction

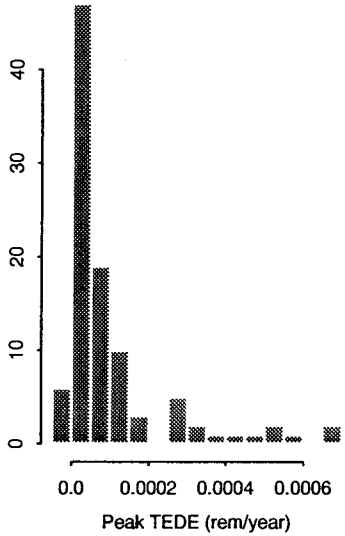
APPENDIX G:

Run: FLTO_Run6

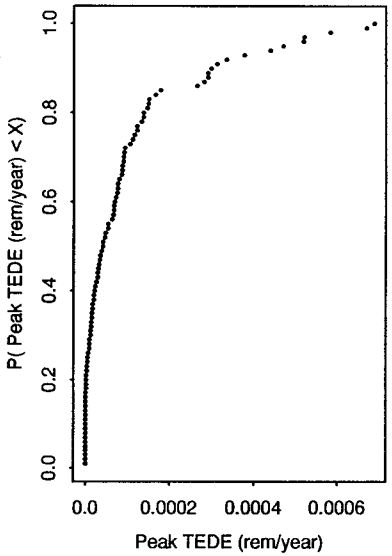
Distance to Focused Group = 20 km
Recurrence Interval = 5,000 years
Only FAULTO with Focused Corrosion
With Backfill

20 km Scenario
Summary Plots for Peak TEDE (rem/year)

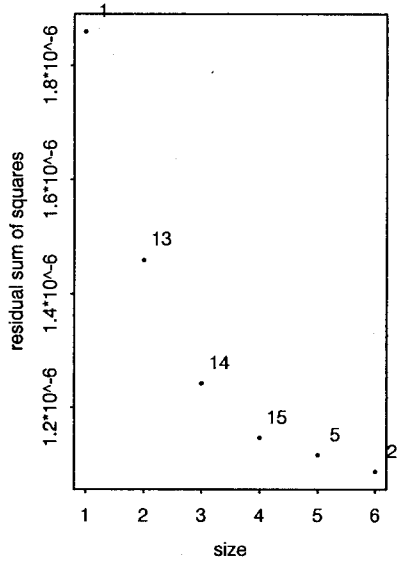
Frequency Distribution



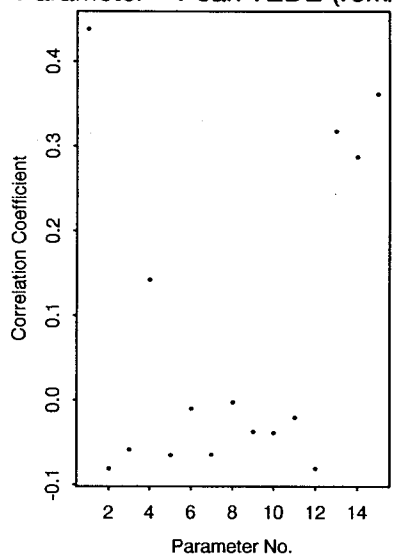
Cumulative Frequency



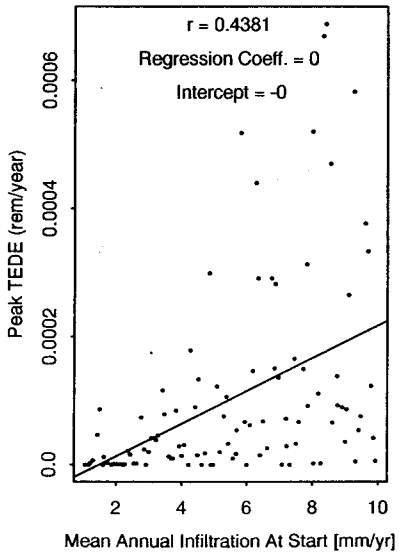
Stepwise Reduction in Error



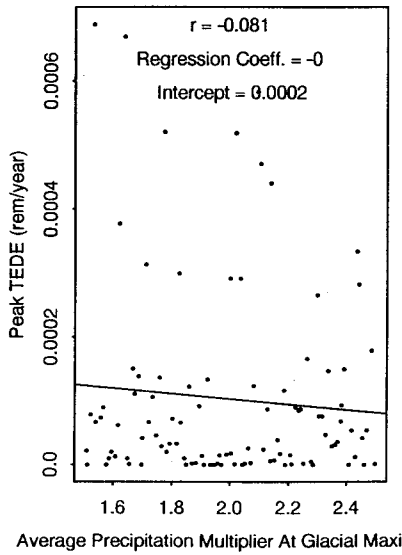
Correlation Coefficients
Parameter ~ Peak TEDE (rem/year)



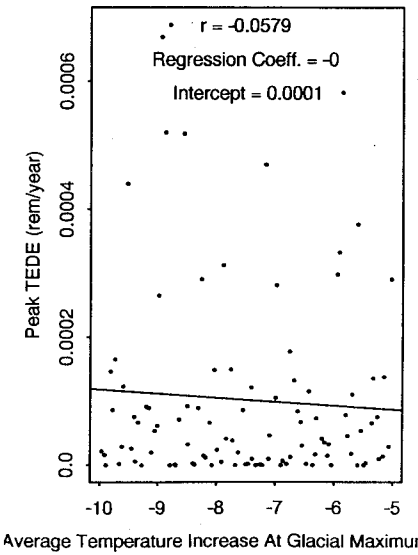
Parameter No. 1



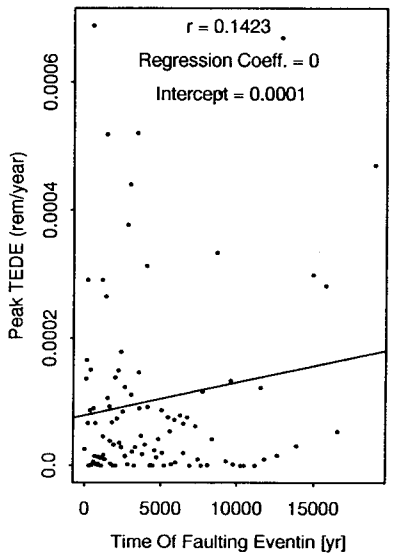
Parameter No. 2



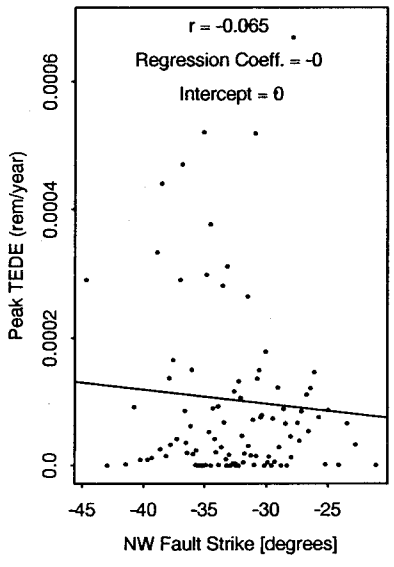
Parameter No. 3



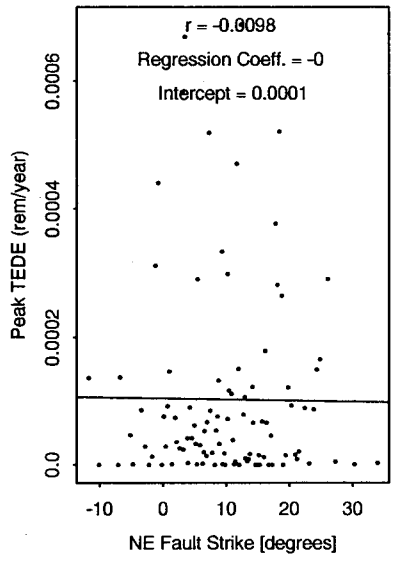
Parameter No. 4



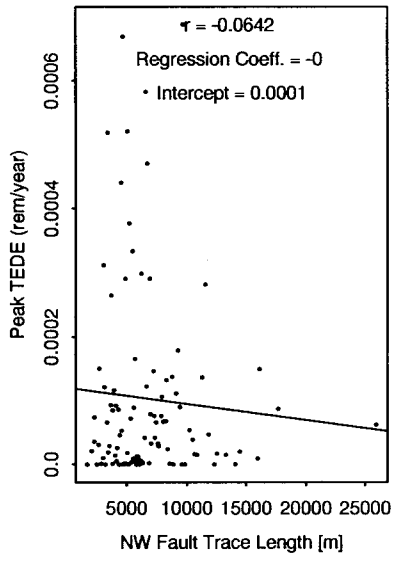
Parameter No. 5



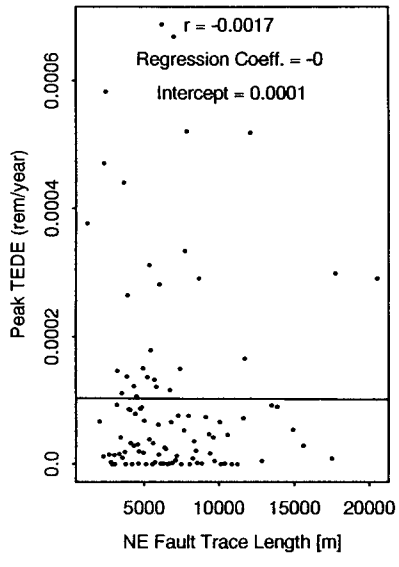
Parameter No. 6



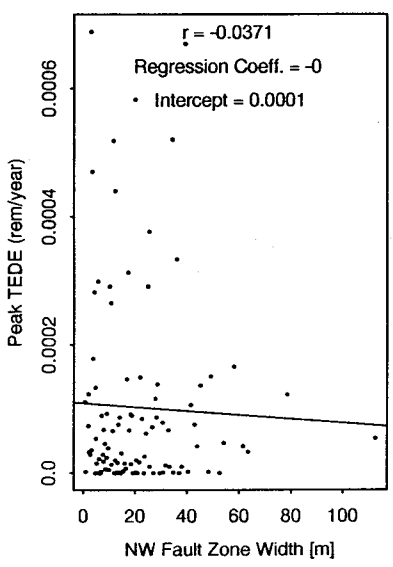
Parameter No. 7



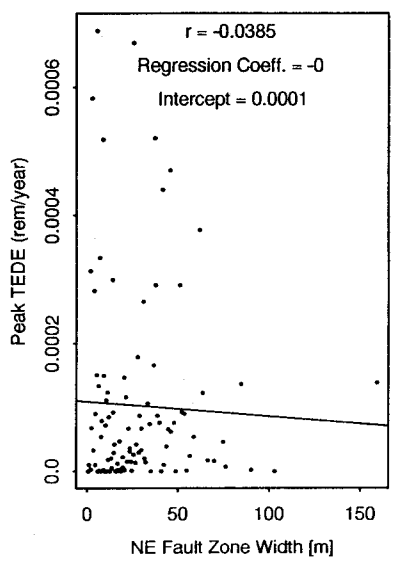
Parameter No. 8



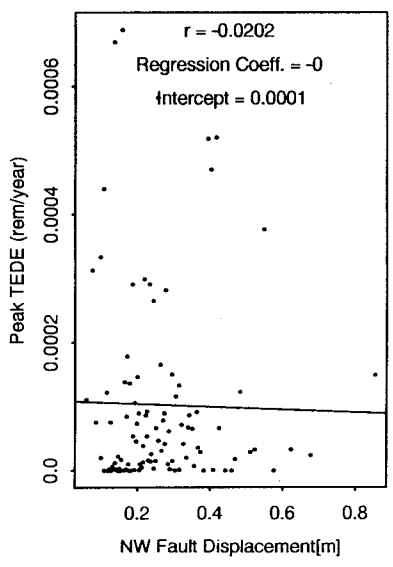
Parameter No. 9



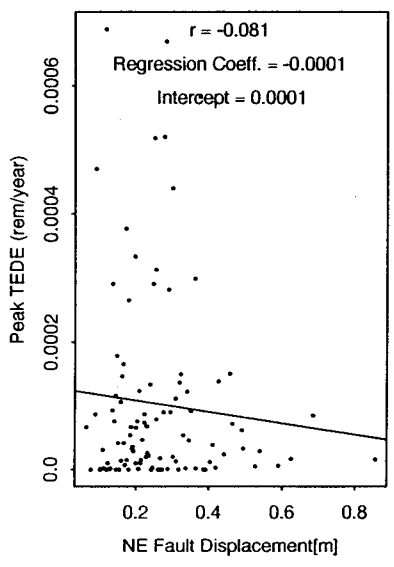
Parameter No. 10



Parameter No. 11

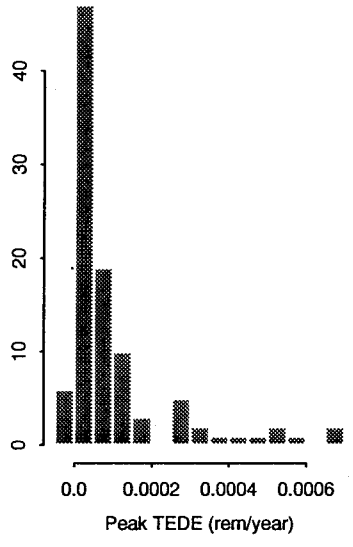


Parameter No. 12

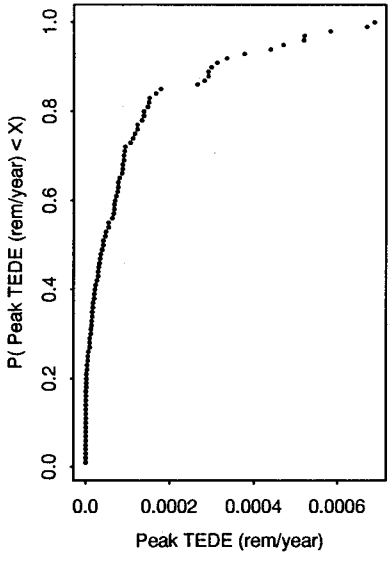


20 km Scenario
Summary Plots for Peak TEDE (rem/year)

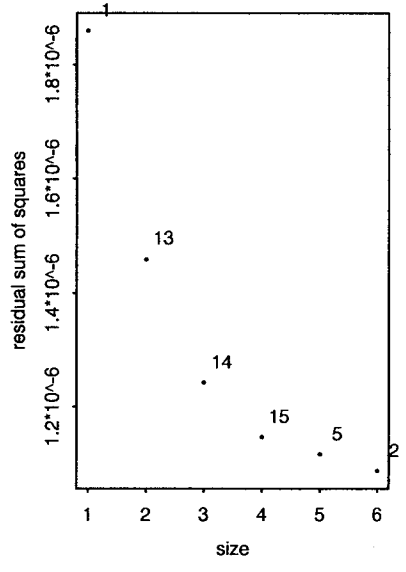
Frequency Distribution



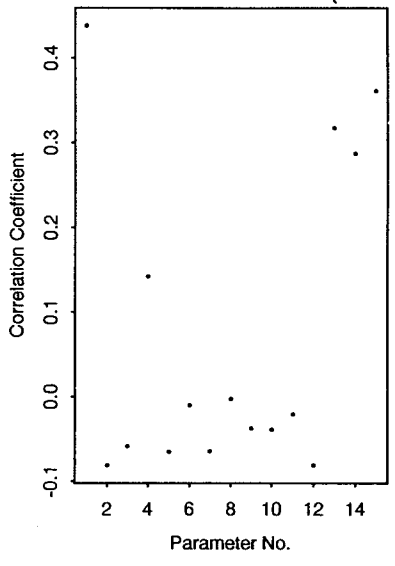
Cumulative Frequency



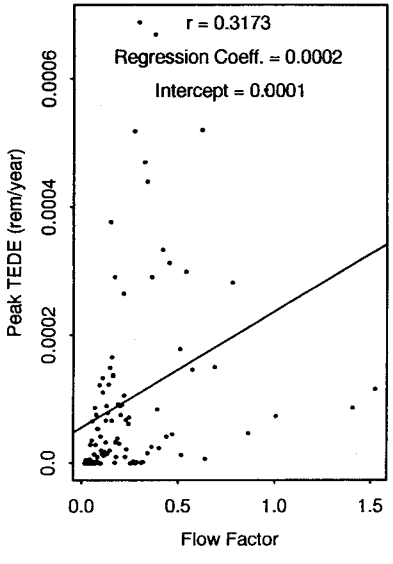
Stepwise Reduction in Error



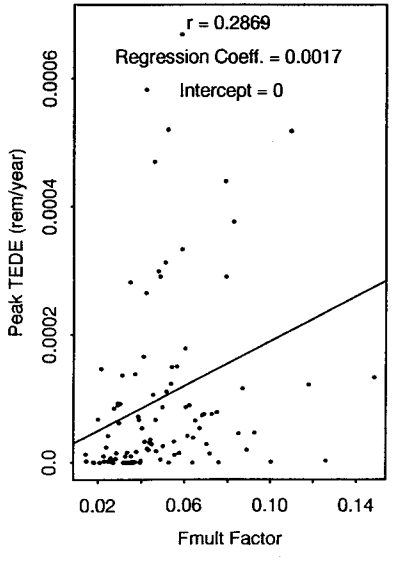
Correlation Coefficients
Parameter ~ Peak TEDE (rem/year)



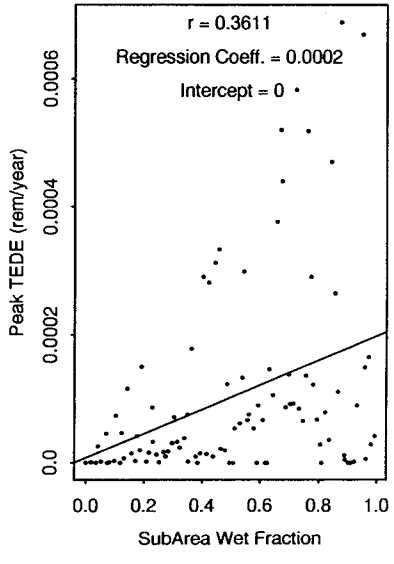
Parameter No. 13



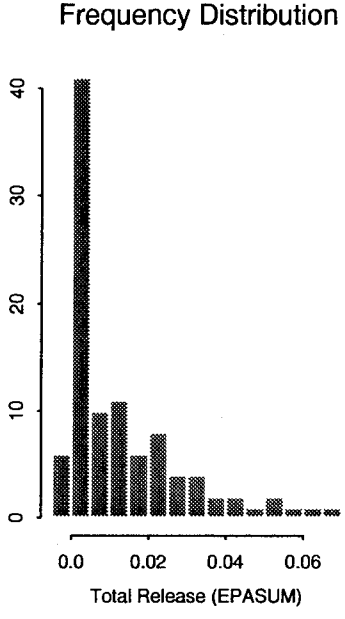
Parameter No. 14

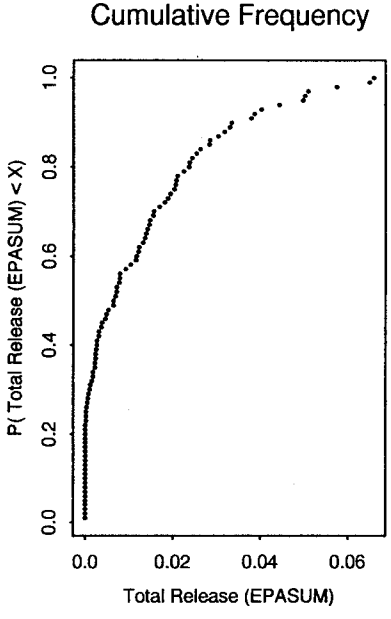


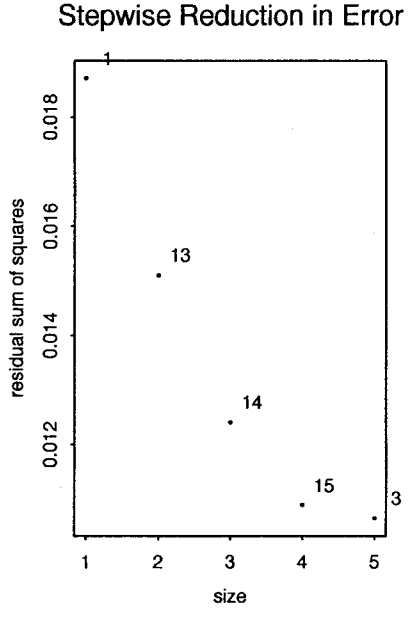
Parameter No. 15

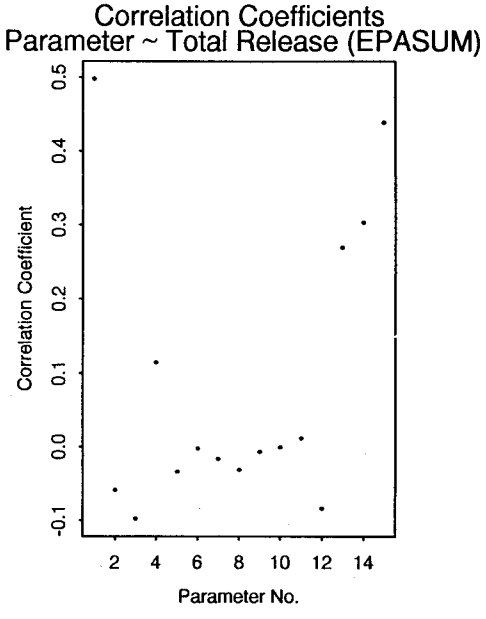


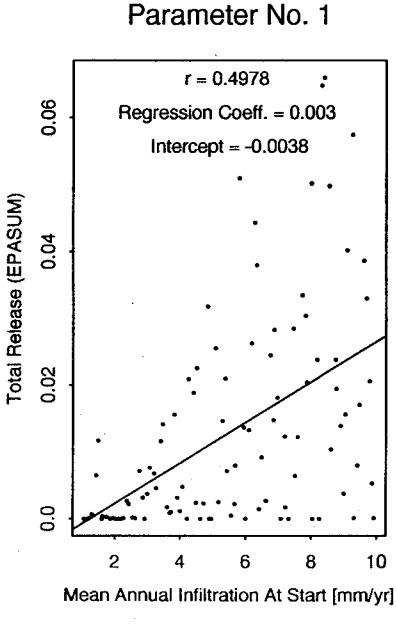
20 km Scenario
Summary Plots for Total Release (EPASUM)

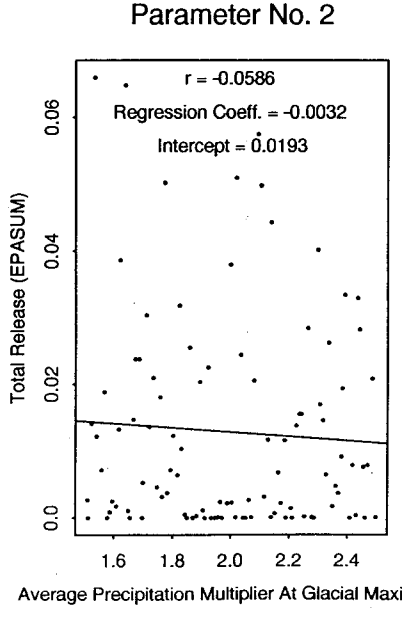


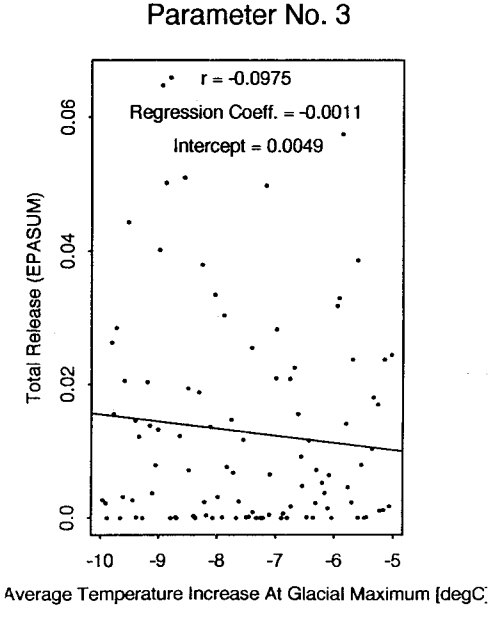


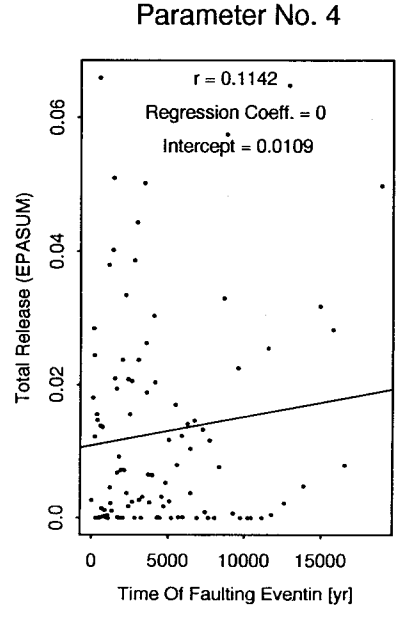




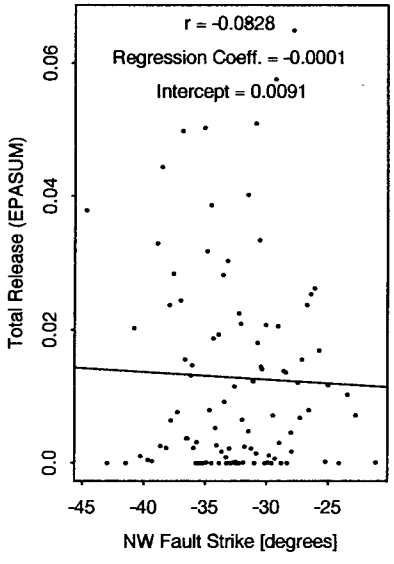




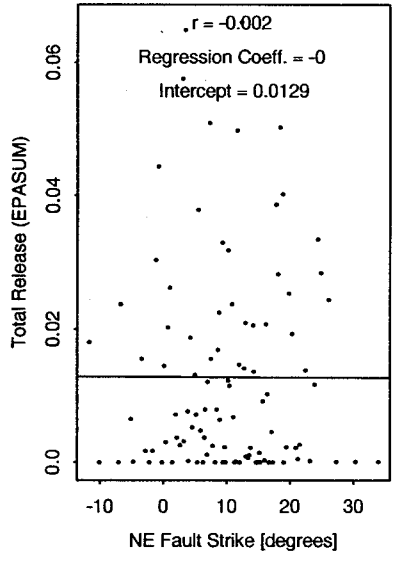




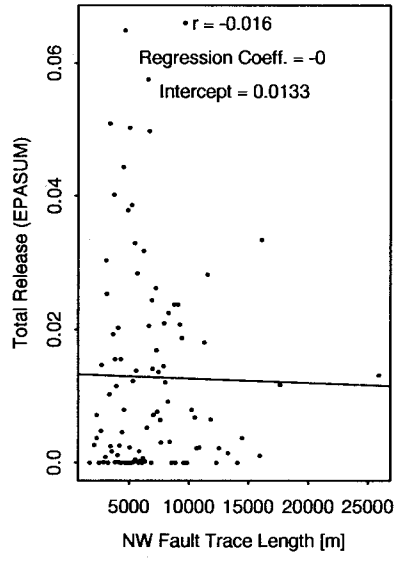
Parameter No. 5



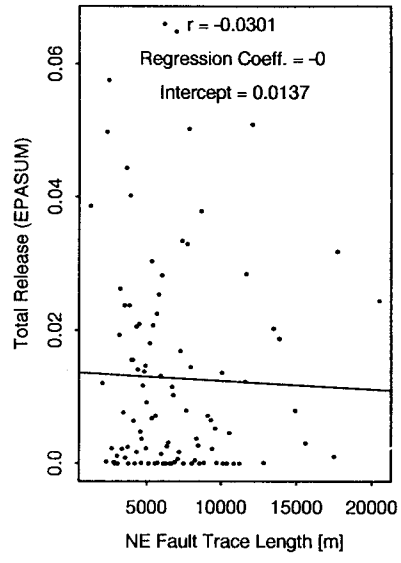
Parameter No. 6



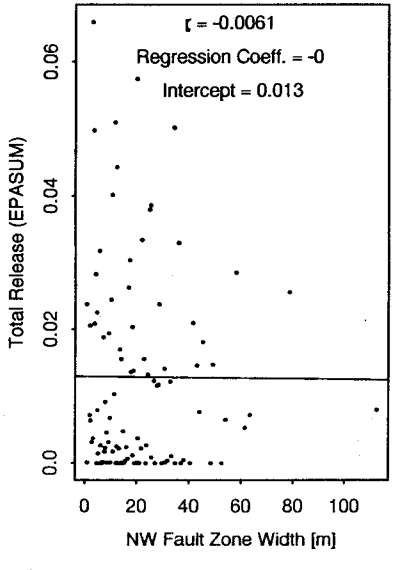
Parameter No. 7



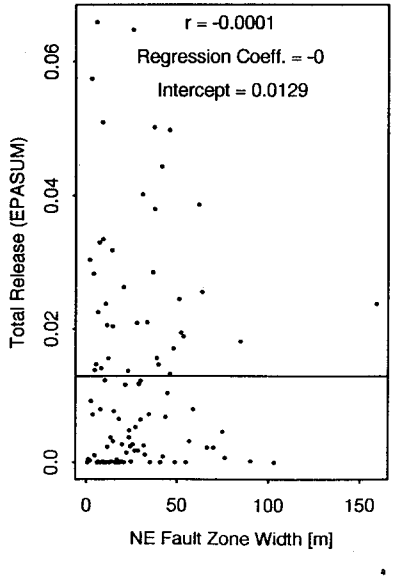
Parameter No. 8



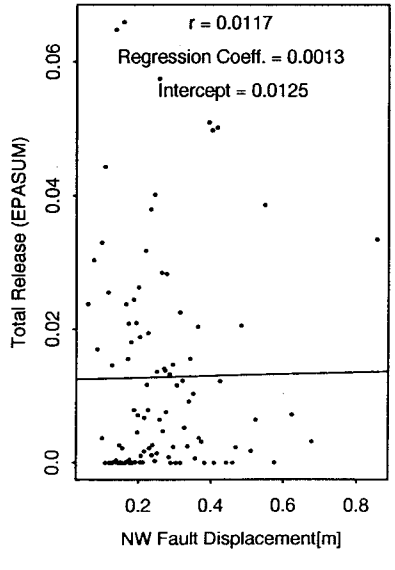
Parameter No. 9



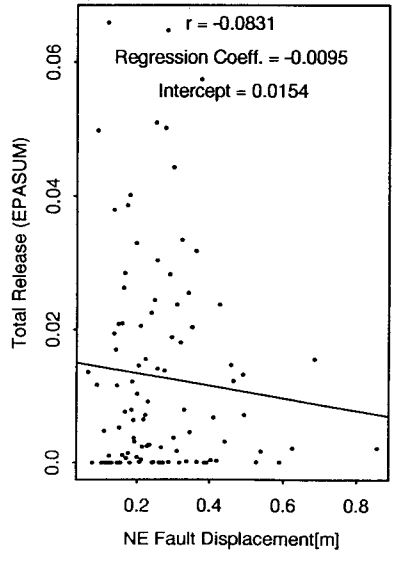
Parameter No. 10

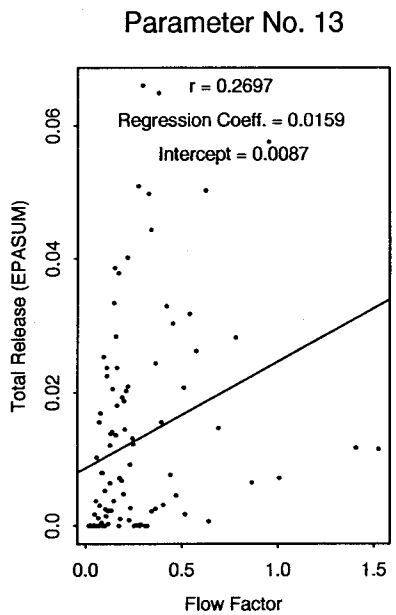


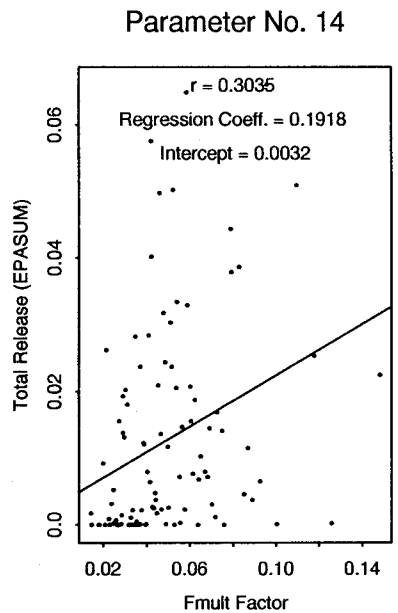
Parameter No. 11

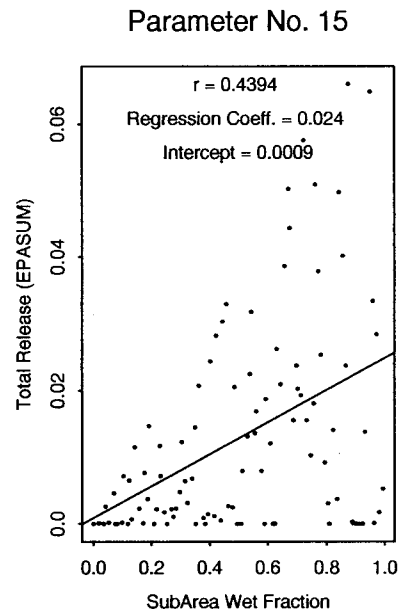


Parameter No. 12



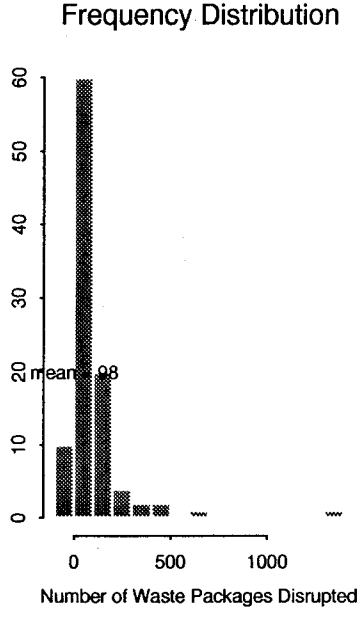

Parameter No. 13
r = 0.2697
Regression Coeff. = 0.0159
Intercept = 0.0087
Total Release (EPASUM)
0.0
0.02
0.04
0.06
0.0
0.5
1.0
1.5
Flow Factor

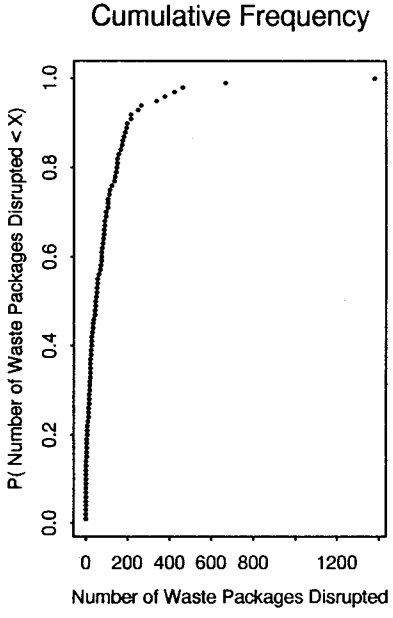

Parameter No. 14
r = 0.3035
Regression Coeff. = 0.1918
Intercept = 0.0032
Total Release (EPASUM)
0.0
0.02
0.04
0.06
0.02
0.06
0.10
0.14
Fmult Factor

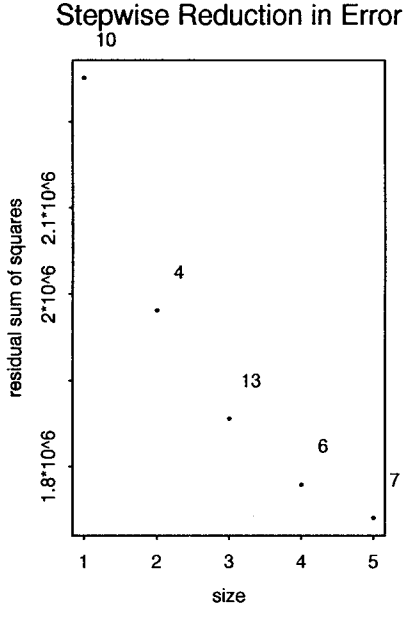

Parameter No. 15
r = 0.4394
Regression Coeff. = 0.024
Intercept = 0.0009
Total Release (EPASUM)
0.0
0.02
0.04
0.06
0.0
0.2
0.4
0.6
0.8
1.0
SubArea Wet Fraction

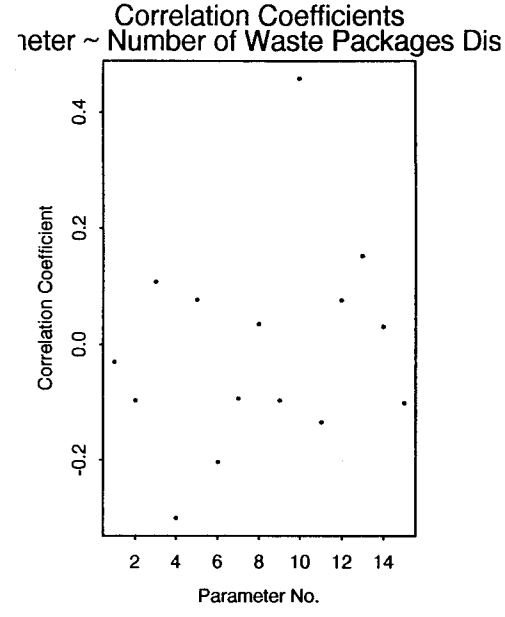
FLTO- Run6

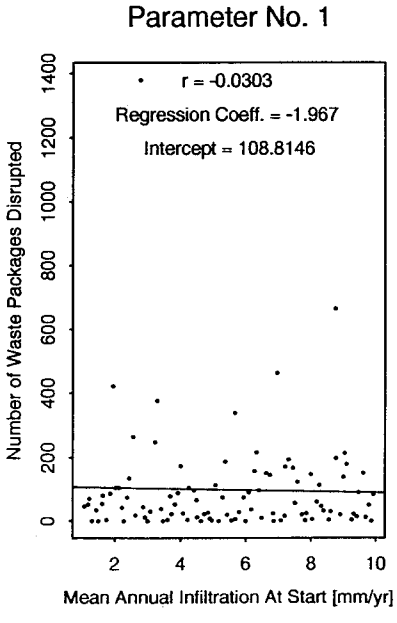
20 km Scenario
Summary Plots for Number of Waste Packages Disrupted

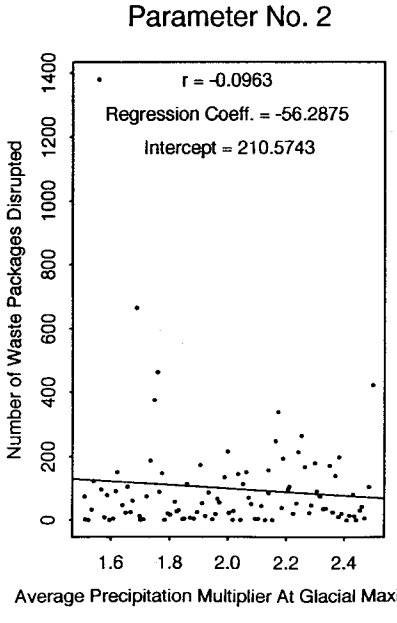


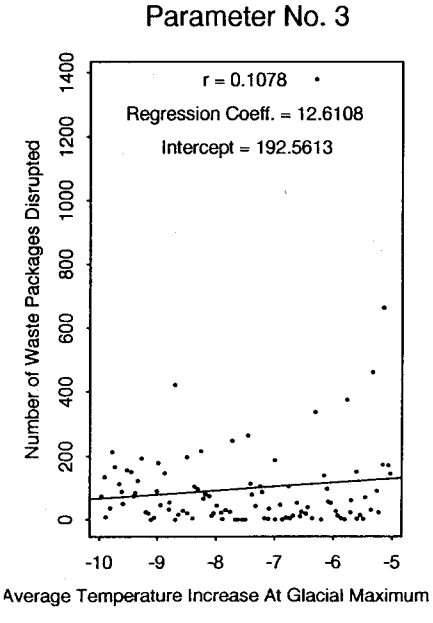


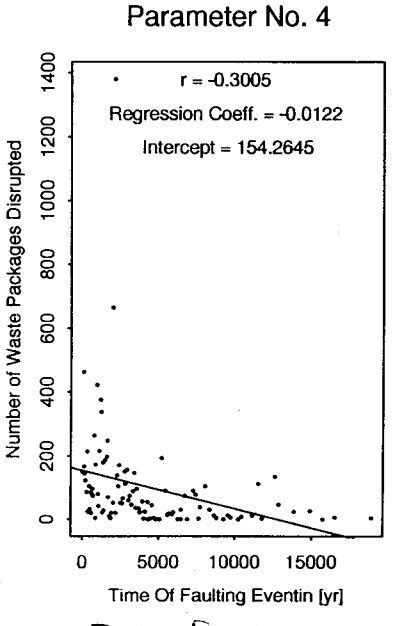




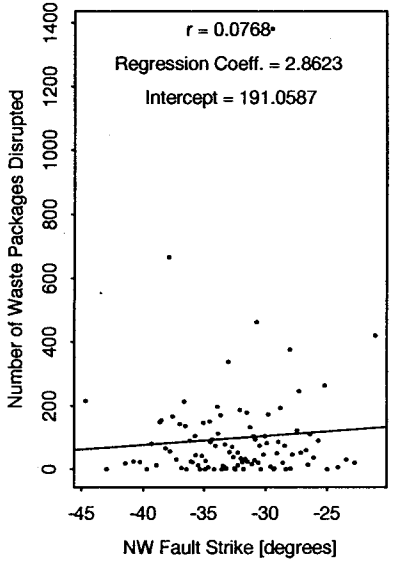




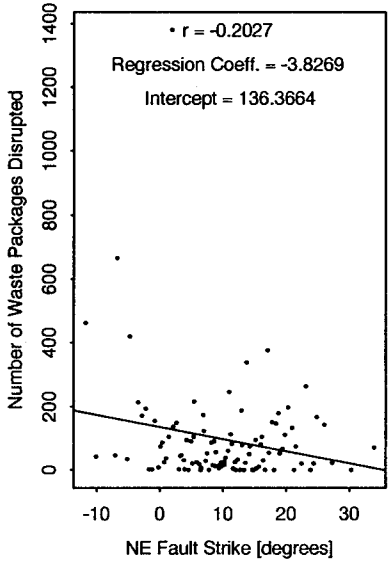




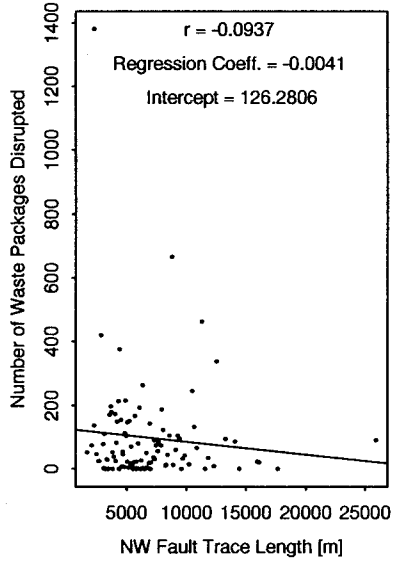
Parameter No. 5



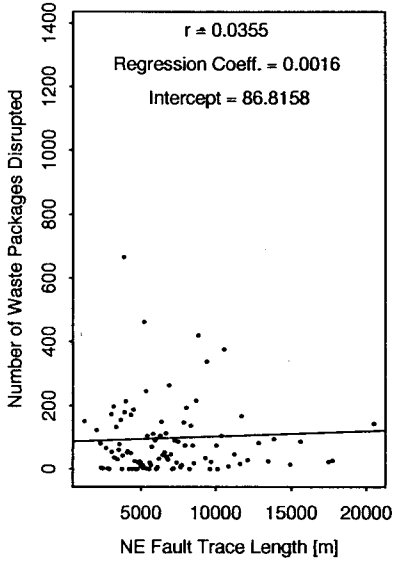
Parameter No. 6



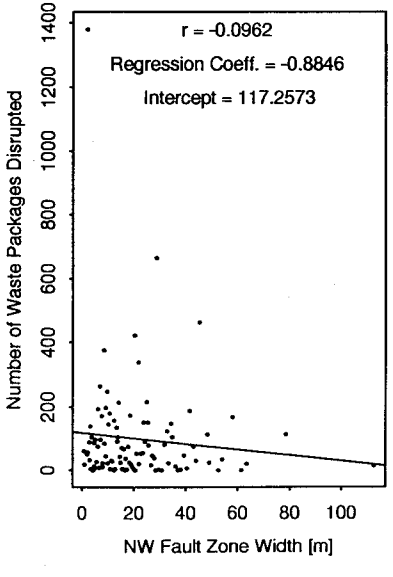
Parameter No. 7



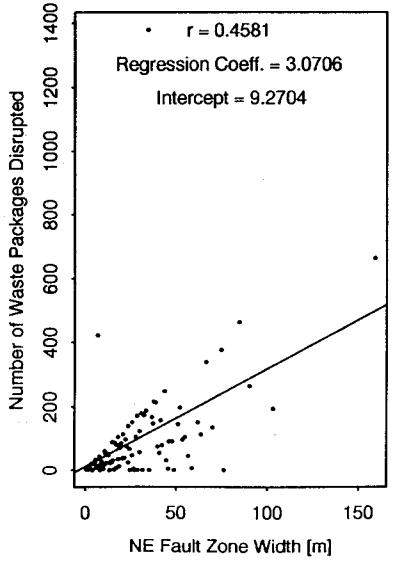
Parameter No. 8



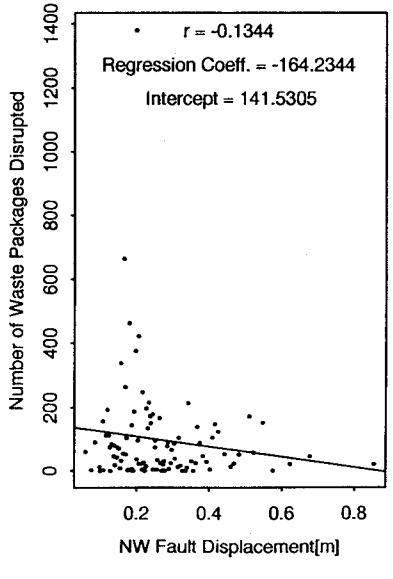
Parameter No. 9



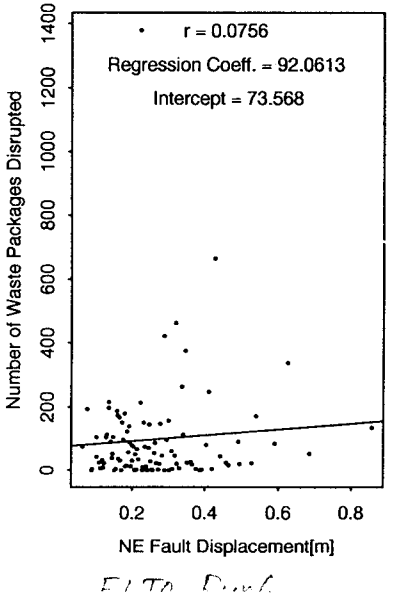
Parameter No. 10

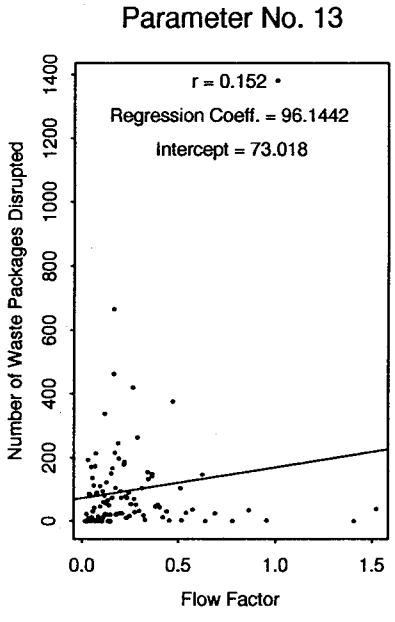


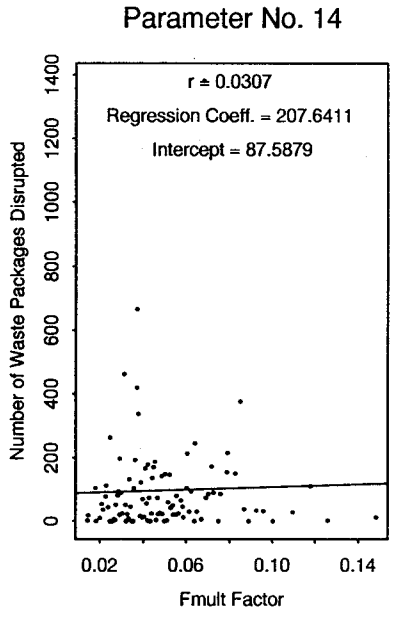
Parameter No. 11

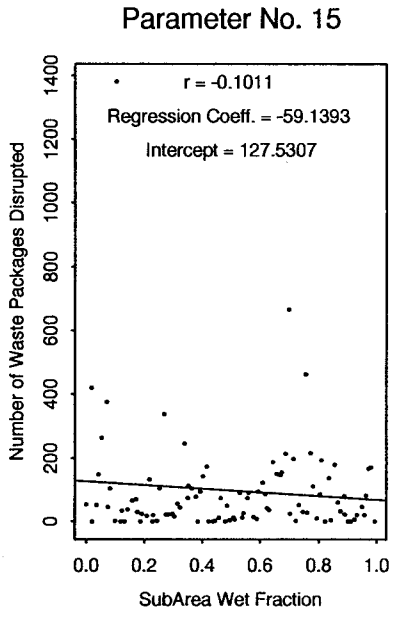


Parameter No. 12




Parameter No. 13
r = 0.152
Regression Coeff. = 96.1442
Intercept = 73.018
Number of Waste Packages Disrupted
0
200
400
600
800
1000
1200
1400
0.0
0.5
1.0
1.5
Flow Factor


Parameter No. 14
r = 0.0307
Regression Coeff. = 207.6411
Intercept = 87.5879
Number of Waste Packages Disrupted
0
200
400
600
800
1000
1200
1400
0.02
0.06
0.10
0.14
Fmult Factor


Parameter No. 15
r = -0.1011
Regression Coeff. = -59.1393
Intercept = 127.5307
Number of Waste Packages Disrupted
0
200
400
600
800
1000
1200
1400
0.0
0.2
0.4
0.6
0.8
1.0
SubArea Wet Fraction

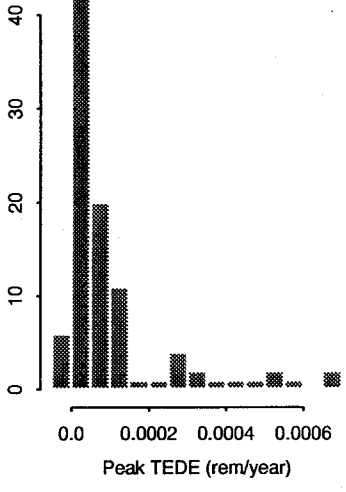
APPENDIX H:

Run: FLTO_Run7

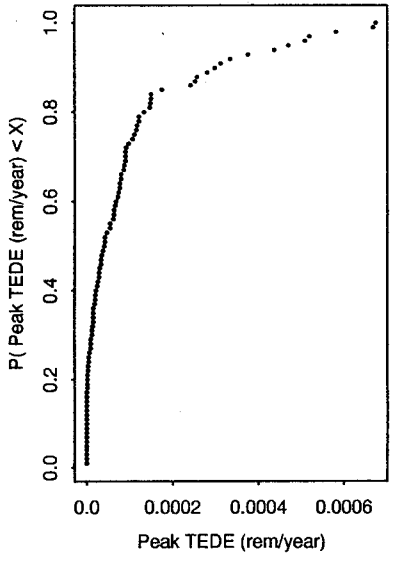
Distance to Focused Group = 20 km
Recurrence Interval = 200,000 years
Only FAULTO with Focused Corrosion
With Backfill

20 km Scenario
Summary Plots for Peak TEDE (rem/year)

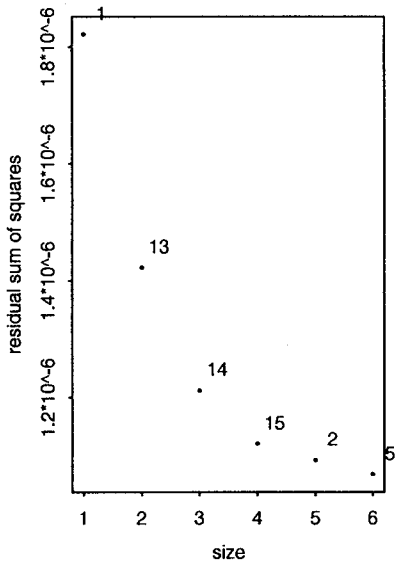
Frequency Distribution



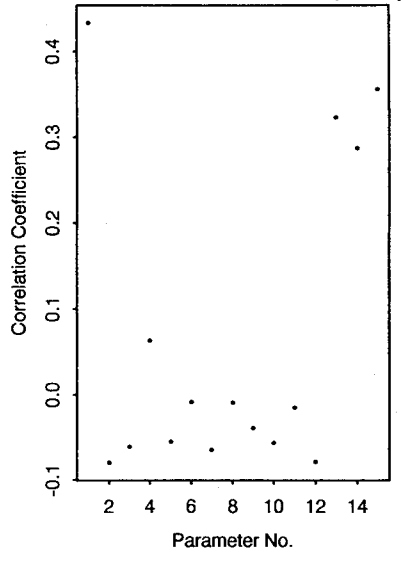
Cumulative Frequency



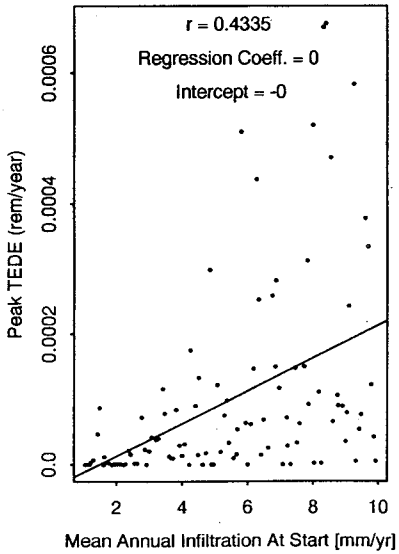
Stepwise Reduction in Error



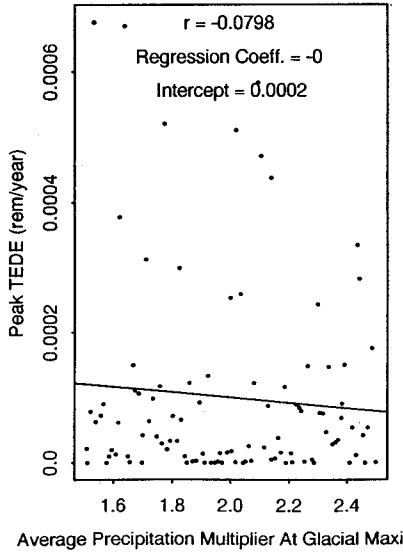
Correlation Coefficients
Parameter ~ Peak TEDE (rem/year)



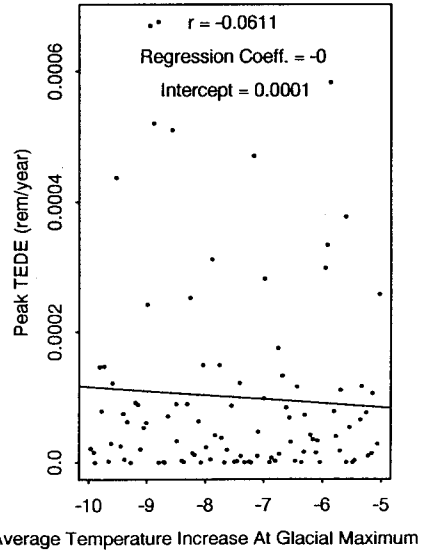
Parameter No. 1



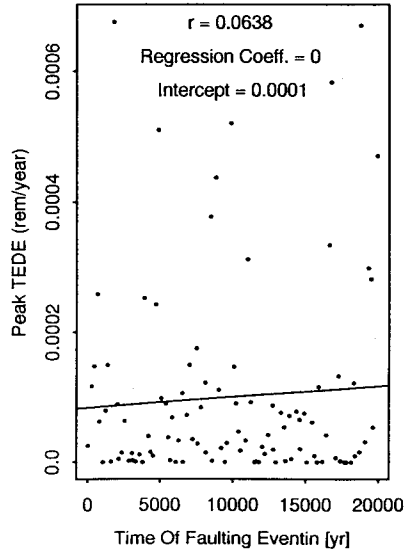
Parameter No. 2



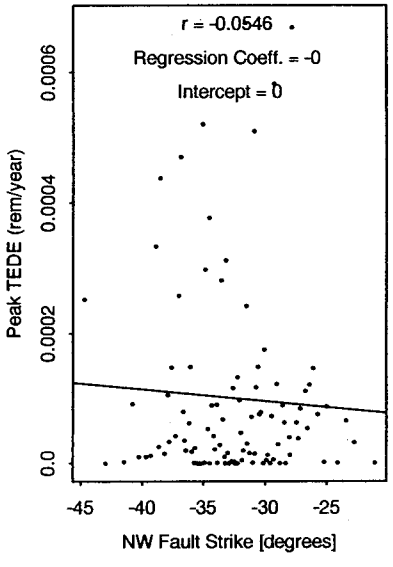
Parameter No. 3



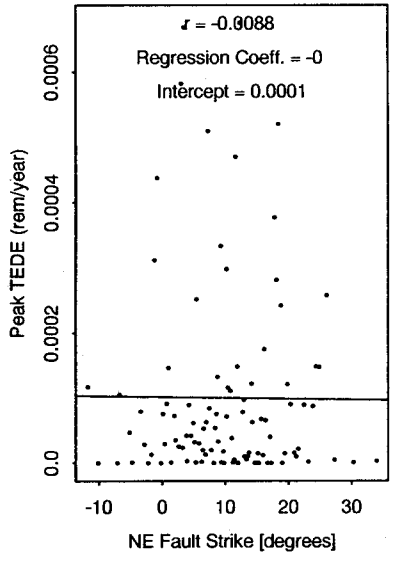
Parameter No. 4



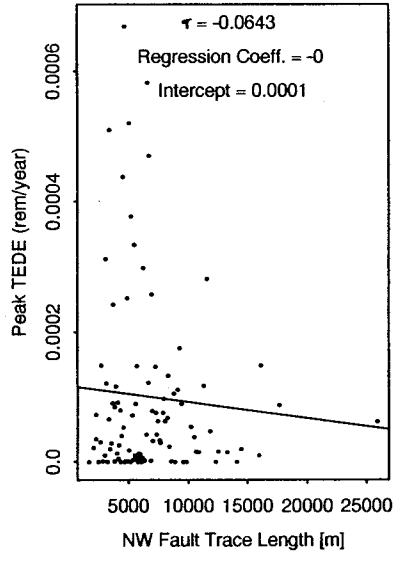
Parameter No. 5



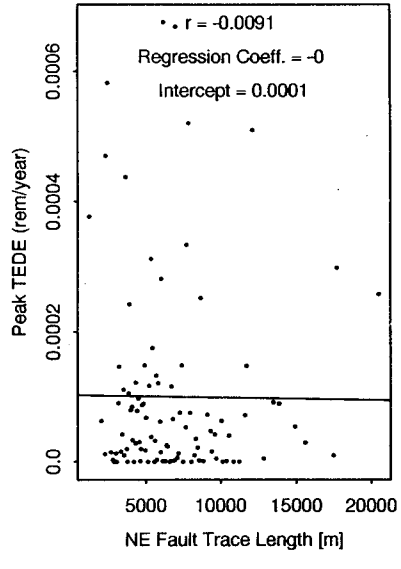
Parameter No. 6



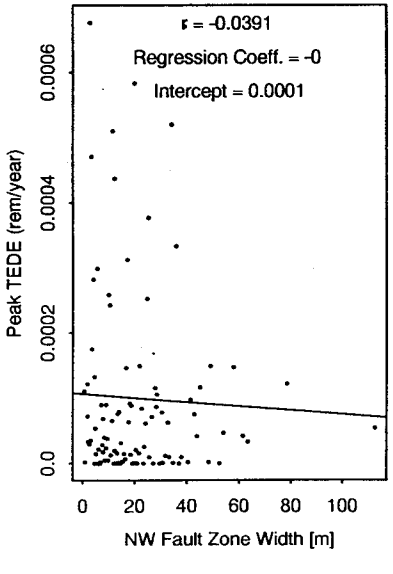
Parameter No. 7



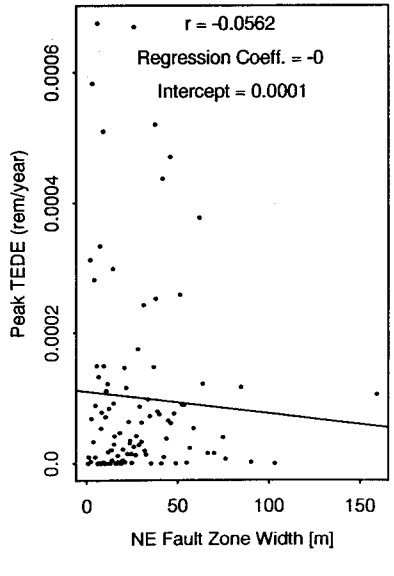
Parameter No. 8



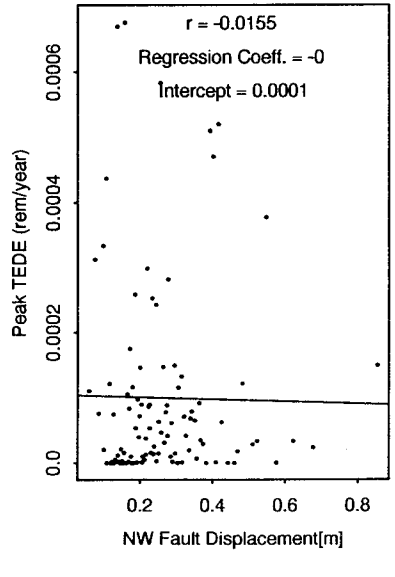
Parameter No. 9



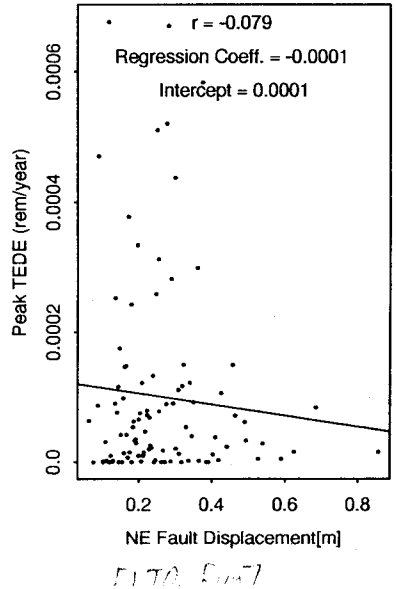
Parameter No. 10



Parameter No. 11

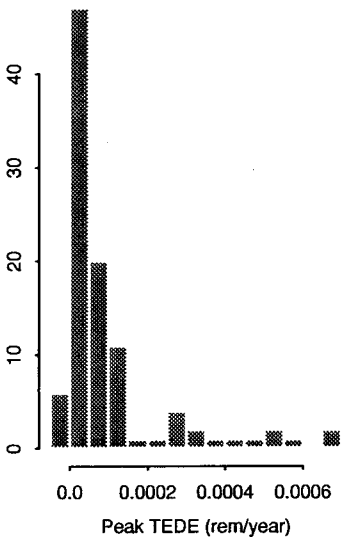


Parameter No. 12

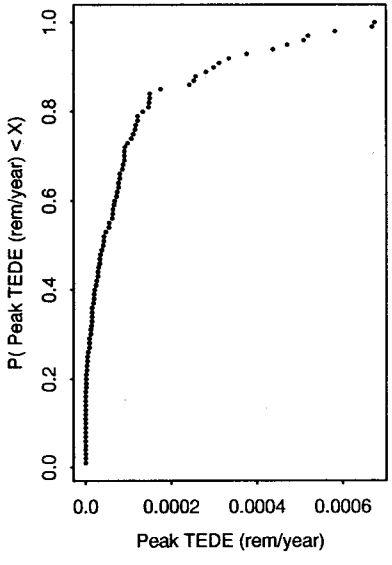


20 km Scenario
Summary Plots for Peak TEDE (rem/year)

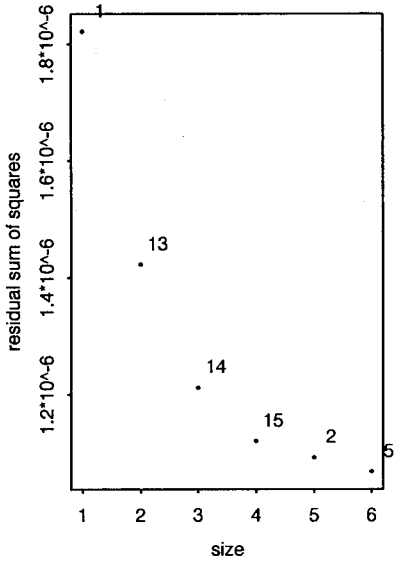
Frequency Distribution



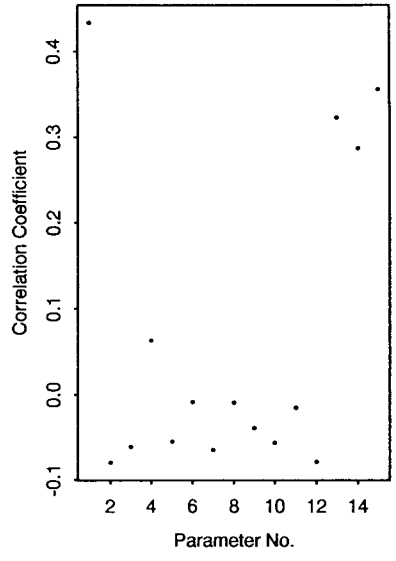
Cumulative Frequency



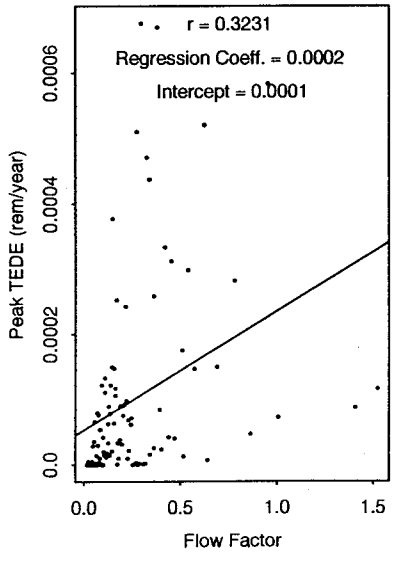
Stepwise Reduction in Error



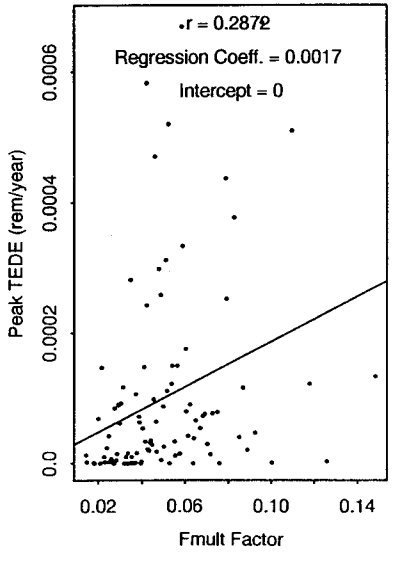
Correlation Coefficients
Parameter ~ Peak TEDE (rem/year)



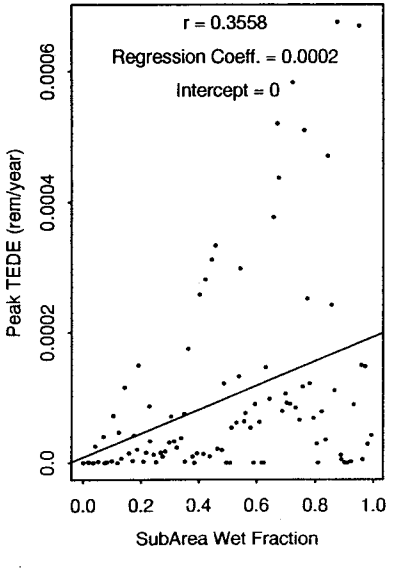
Parameter No. 13



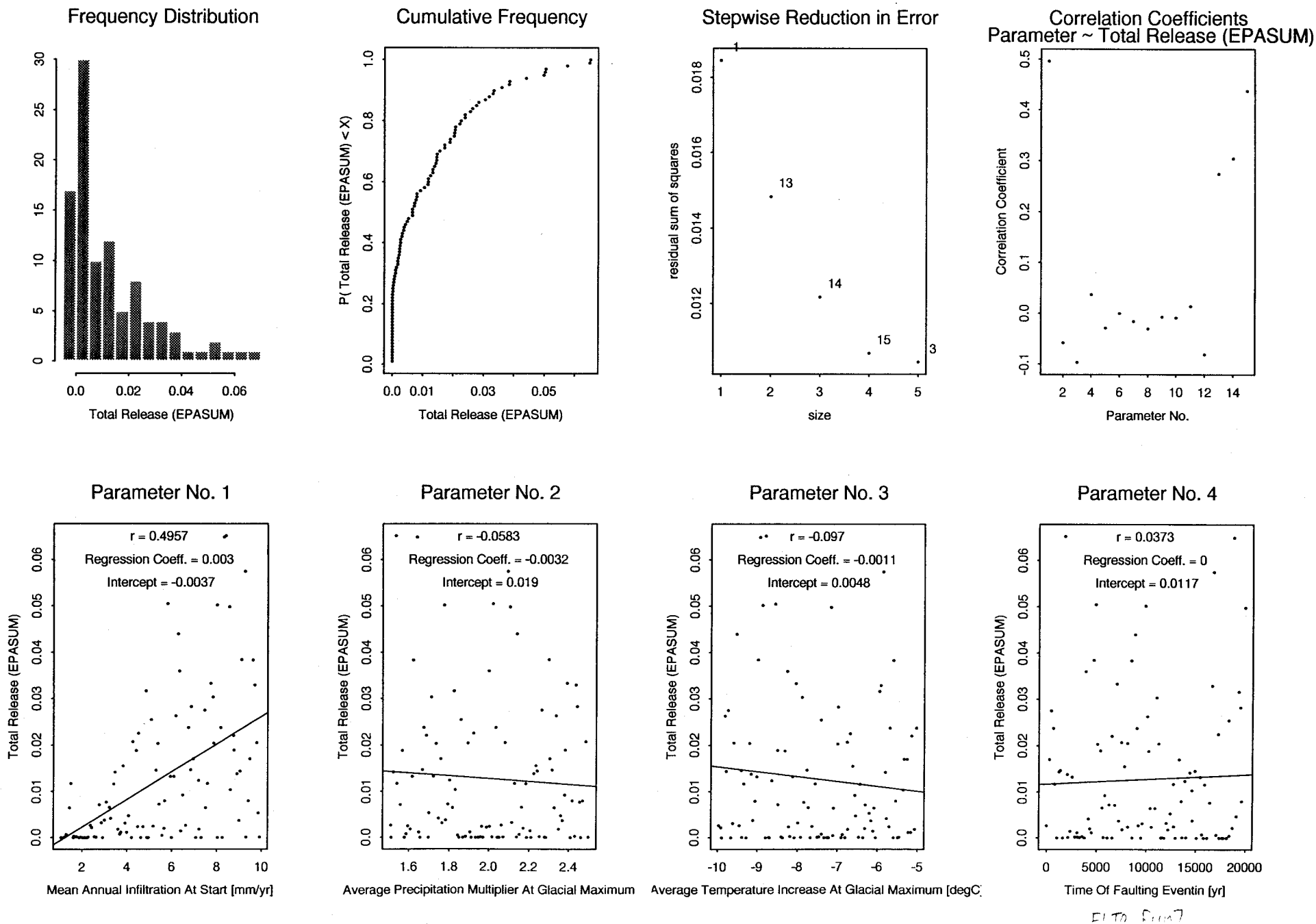
Parameter No. 14

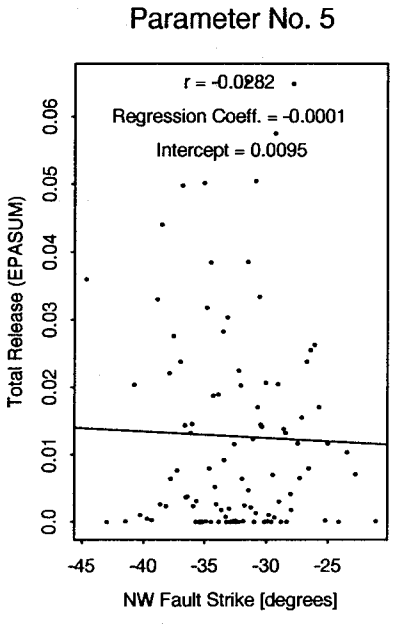


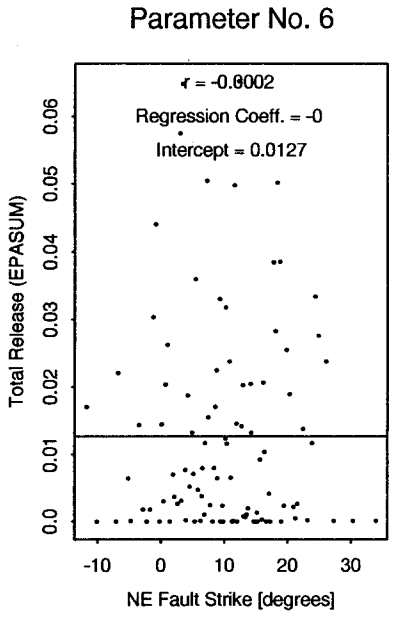
Parameter No. 15

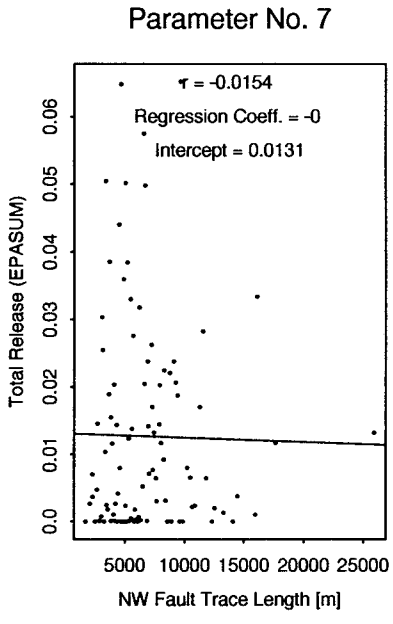


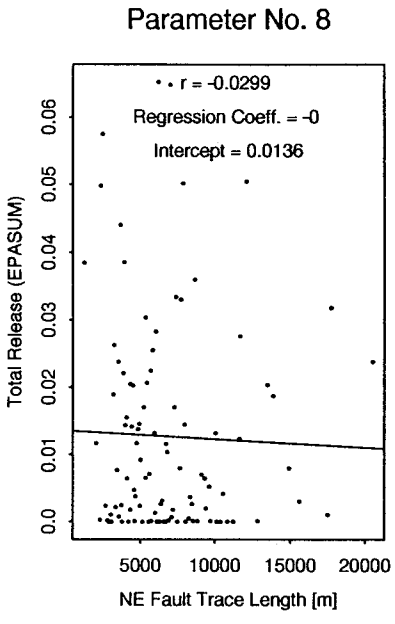
20 km Scenario
Summary Plots for Total Release (EPASUM)

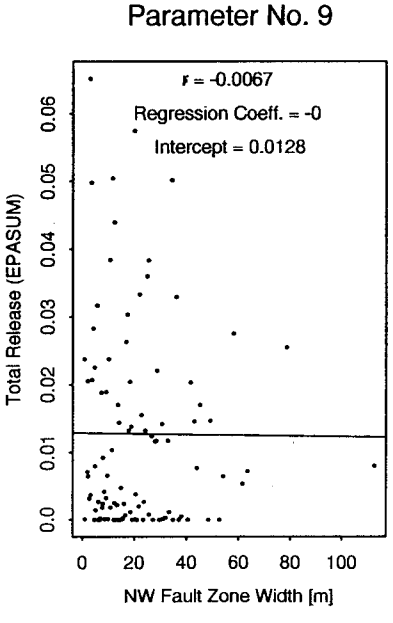


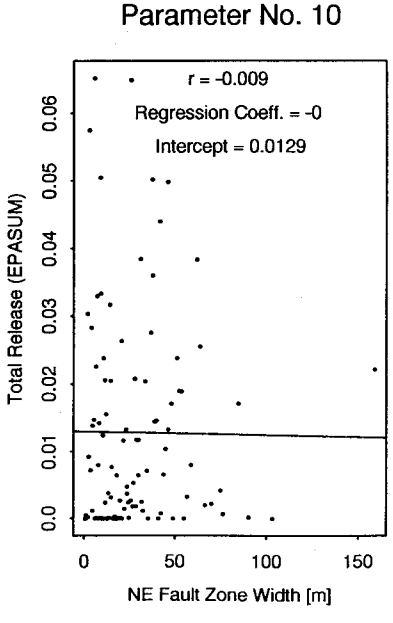

Parameter No. 5
r = -0.0282
Regression Coeff. = -0.0001
Intercept = 0.0095
Total Release (EPASUM)
0.0
0.01
0.02
0.03
0.04
0.05
0.06
-45
-40
-35
-30
-25
NW Fault Strike [degrees]

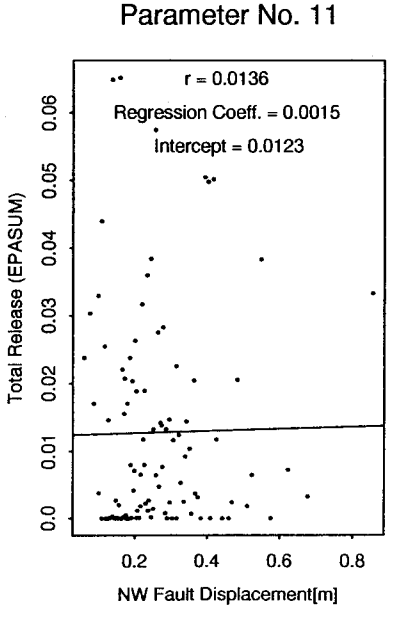

Parameter No. 6
r = -0.0002
Regression Coeff. = -0
Intercept = 0.0127
Total Release (EPASUM)
0.0
0.01
0.02
0.03
0.04
0.05
0.06
-10
0
10
20
30
NE Fault Strike [degrees]

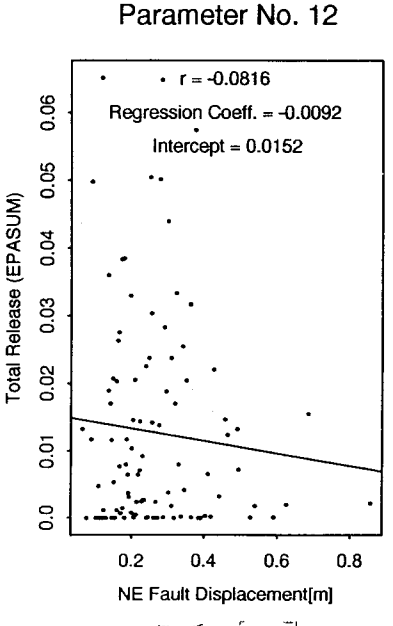

Parameter No. 7
r = -0.0154
Regression Coeff. = -0
Intercept = 0.0131
Total Release (EPASUM)
0.0
0.01
0.02
0.03
0.04
0.05
0.06
5000
10000
15000
20000
25000
NW Fault Trace Length [m]

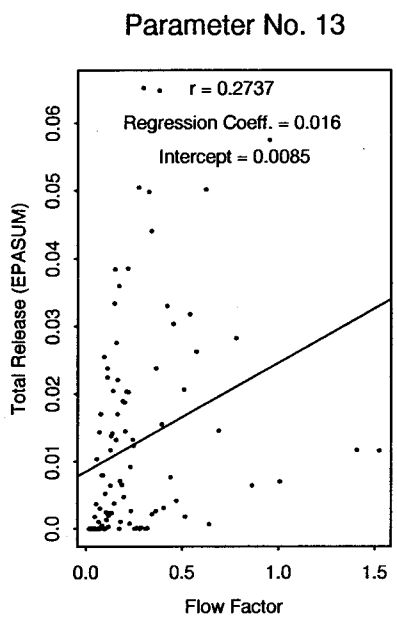

Parameter No. 8
r = -0.0299
Regression Coeff. = -0
Intercept = 0.0136
Total Release (EPASUM)
0.0
0.01
0.02
0.03
0.04
0.05
0.06
5000
10000
15000
20000
NE Fault Trace Length [m]

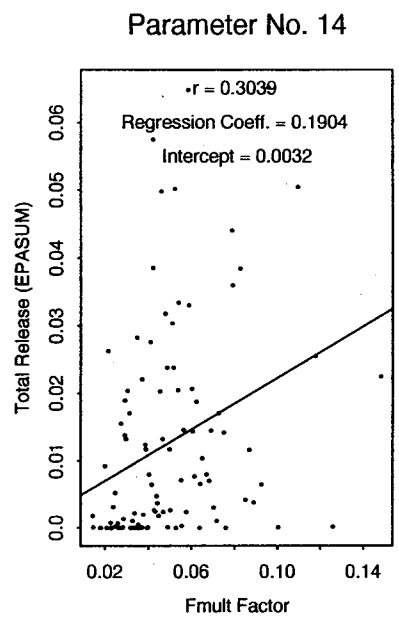

Parameter No. 9
r = -0.0067
Regression Coeff. = -0
Intercept = 0.0128
Total Release (EPASUM)
0.0
0.01
0.02
0.03
0.04
0.05
0.06
0
20
40
60
80
100
NW Fault Zone Width [m]

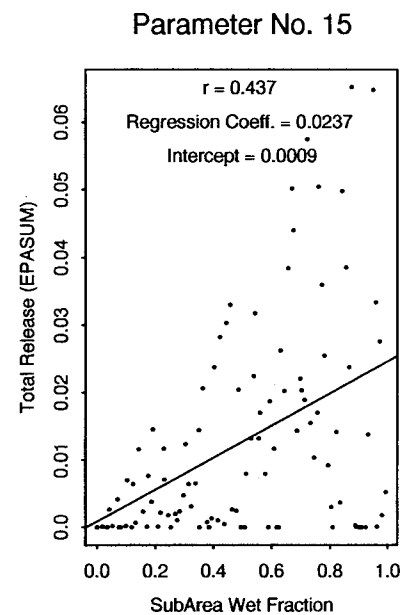

Parameter No. 10
r = -0.009
Regression Coeff. = -0
Intercept = 0.0129
Total Release (EPASUM)
0.0
0.01
0.02
0.03
0.04
0.05
0.06
0
50
100
150
NE Fault Zone Width [m]


Parameter No. 11
r = 0.0136
Regression Coeff. = 0.0015
Intercept = 0.0123
Total Release (EPASUM)
0.0
0.01
0.02
0.03
0.04
0.05
0.06
0.2
0.4
0.6
0.8
NW Fault Displacement[m]


Parameter No. 12
r = -0.0816
Regression Coeff. = -0.0092
Intercept = 0.0152
Total Release (EPASUM)
0.0
0.01
0.02
0.03
0.04
0.05
0.06
0.2
0.4
0.6
0.8
NE Fault Displacement[m]

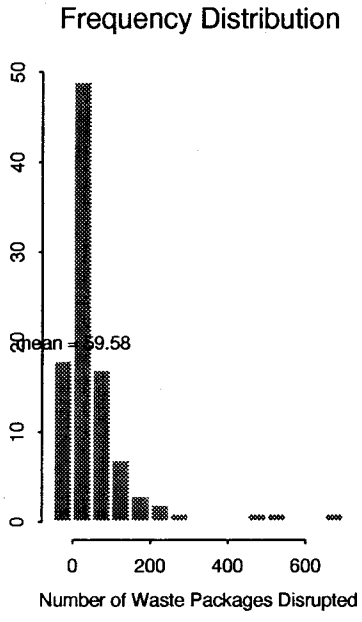

Parameter No. 13
r = 0.2737
Regression Coeff. = 0.016
Intercept = 0.0085
Total Release (EPASUM)
0.0
0.01
0.02
0.03
0.04
0.05
0.06
0.0
0.5
1.0
1.5
Flow Factor

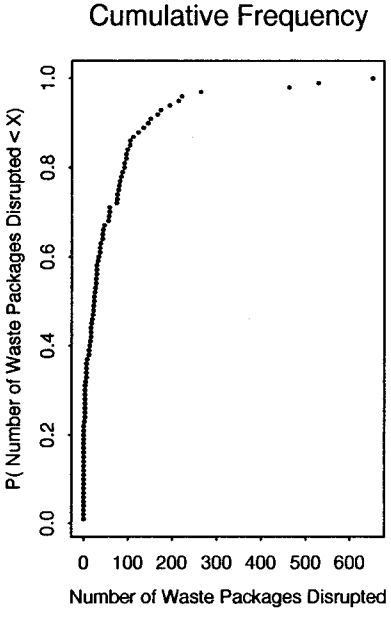

Parameter No. 14
r = 0.3039
Regression Coeff. = 0.1904
Intercept = 0.0032
Total Release (EPASUM)
0.0
0.01
0.02
0.03
0.04
0.05
0.06
0.02
0.06
0.10
0.14
Fmult Factor

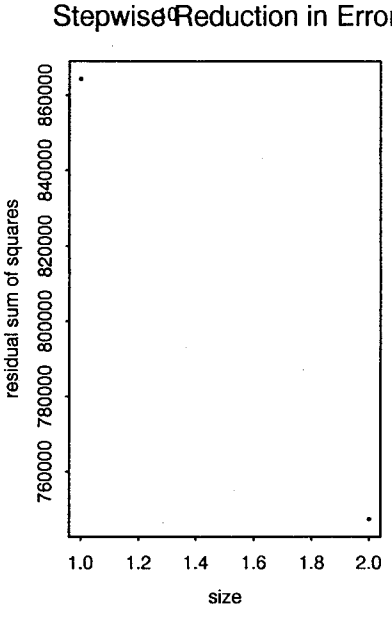

Parameter No. 15
r = 0.437
Regression Coeff. = 0.0237
Intercept = 0.0009
Total Release (EPASUM)
0.0
0.01
0.02
0.03
0.04
0.05
0.06
0.0
0.2
0.4
0.6
0.8
1.0
SubArea Wet Fraction

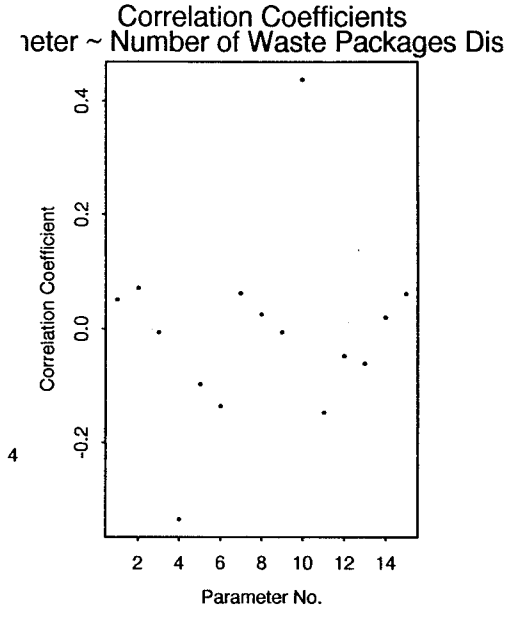
FITD Run 7

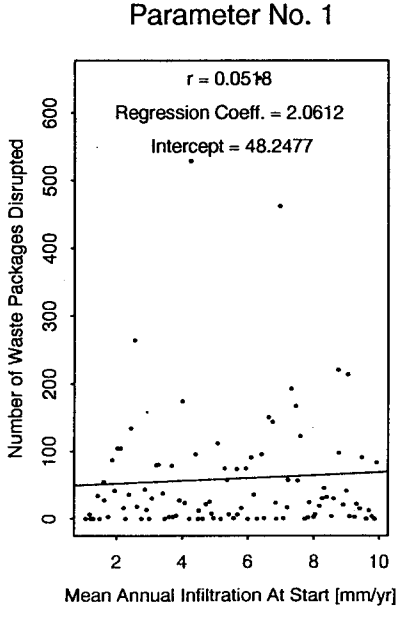
20 km Scenario
Summary Plots for Number of Waste Packages Disrupted

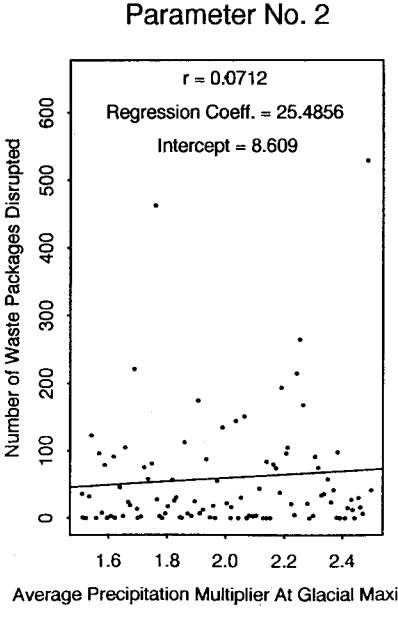


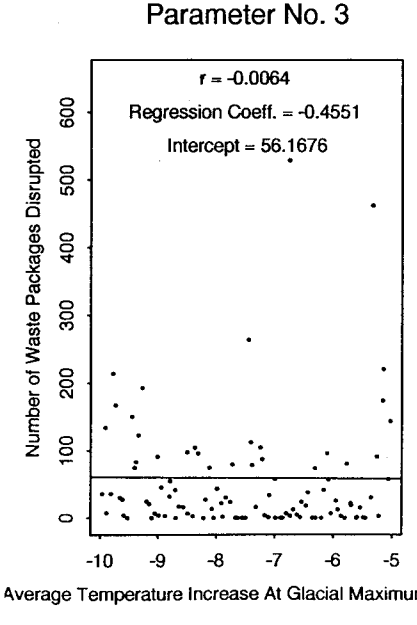


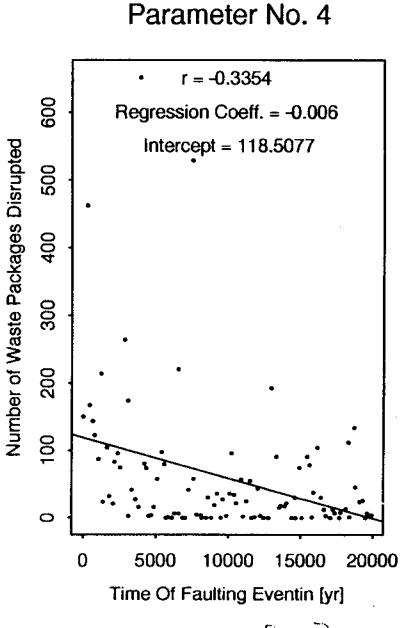




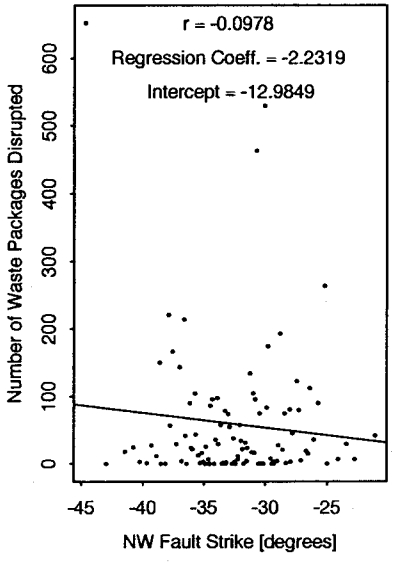




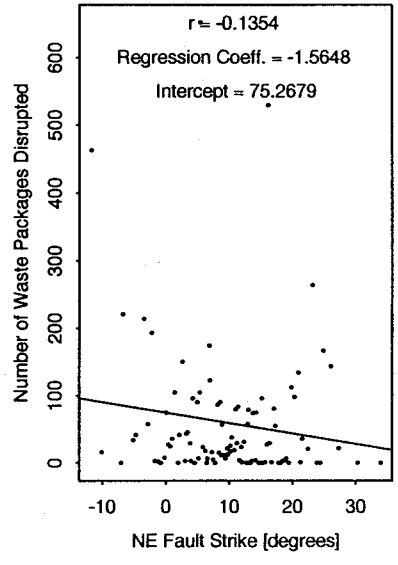




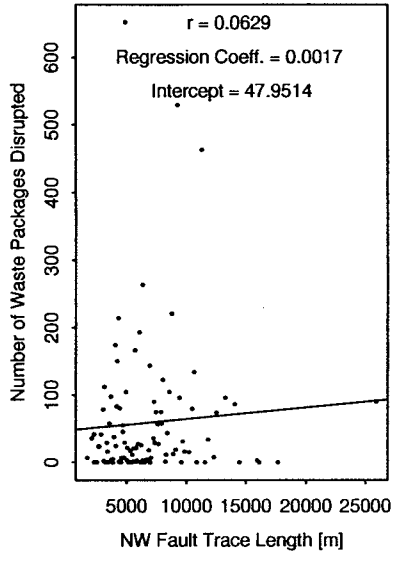
Parameter No. 5



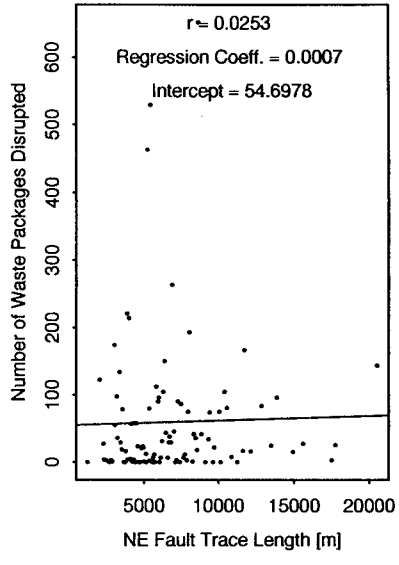
Parameter No. 6



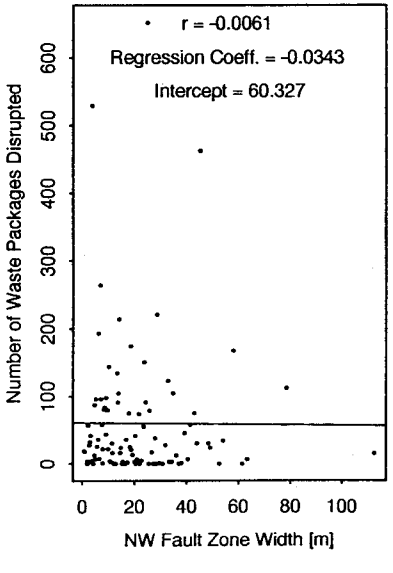
Parameter No. 7



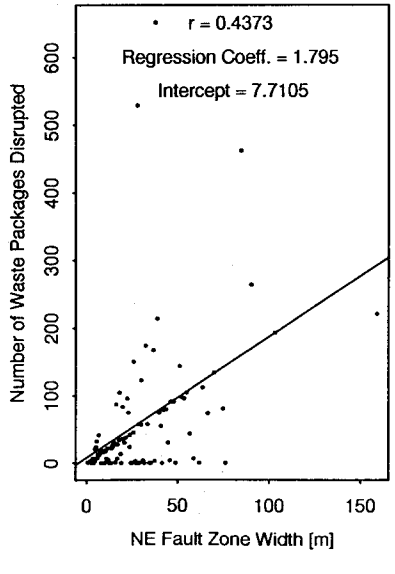
Parameter No. 8



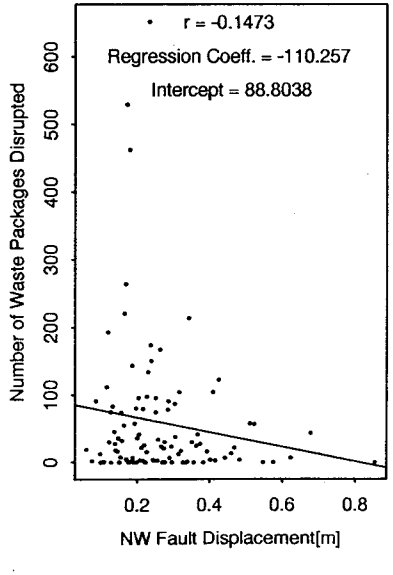
Parameter No. 9



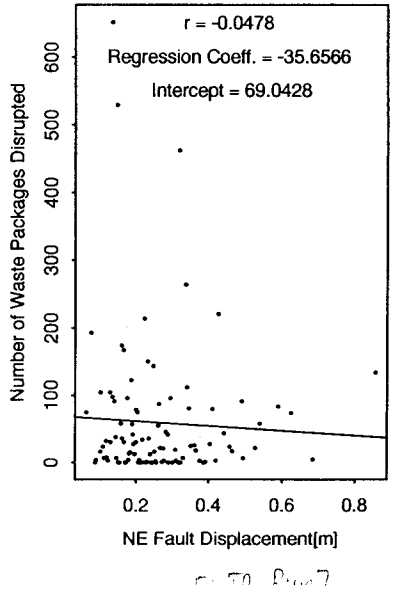
Parameter No. 10



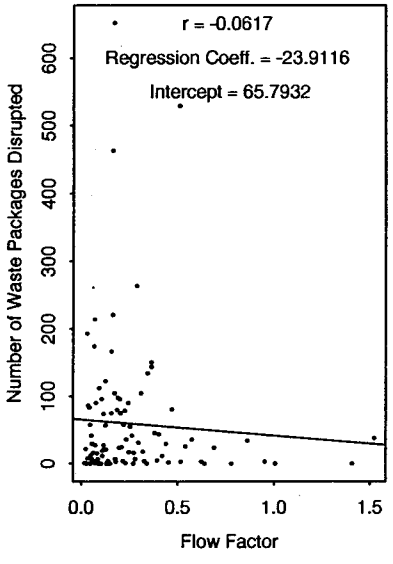
Parameter No. 11



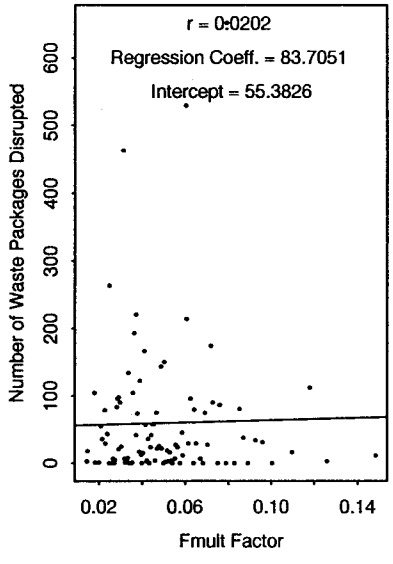
Parameter No. 12



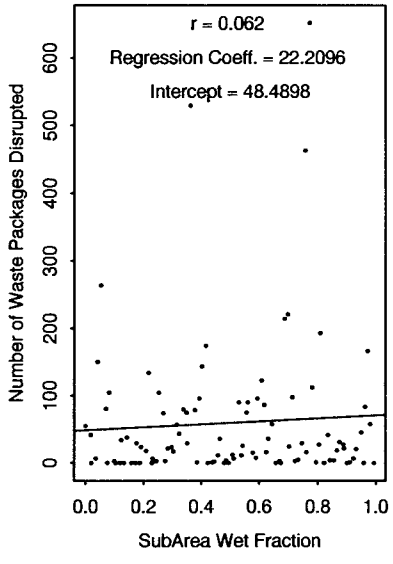
Parameter No. 13



Parameter No. 14



Parameter No. 15



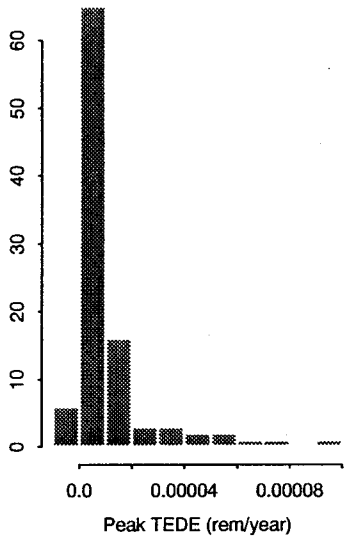
APPENDIX I:

Run: FLTO_Run8

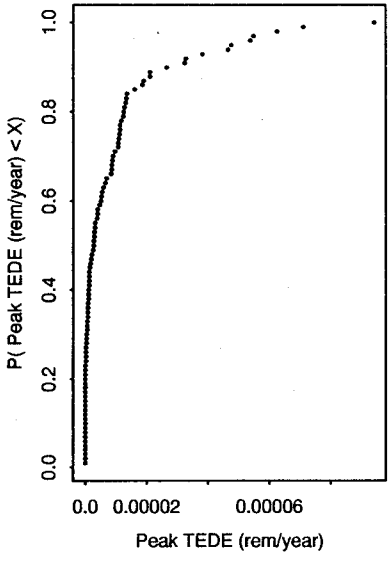
Distance to Focused Group = 20 km
Recurrence Interval = 5,000 years
Only FAULTO with Diffused Corrosion
With Backfill

20 km Scenario
Summary Plots for Peak TEDE (rem/year)

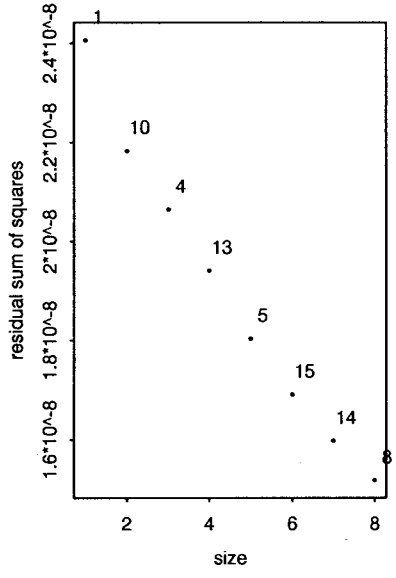
Frequency Distribution



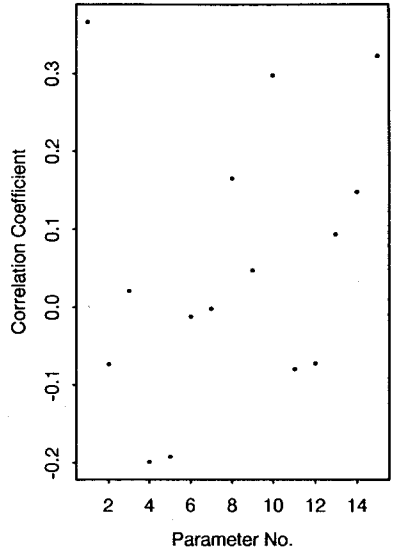
Cumulative Frequency



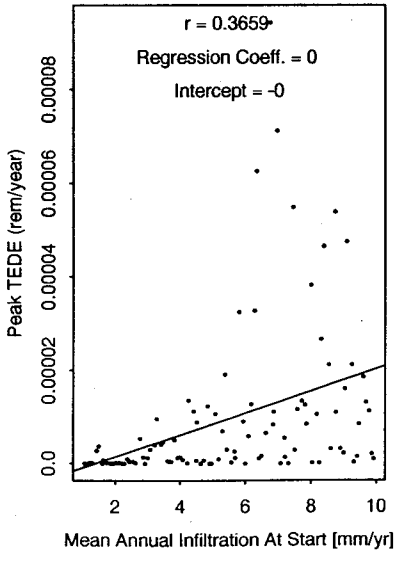
Stepwise Reduction in Error



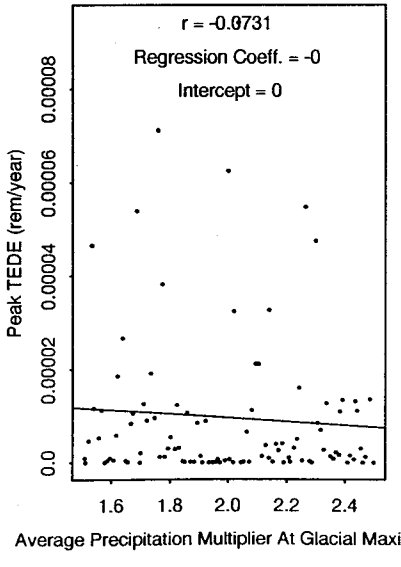
Correlation Coefficients
Parameter ~ Peak TEDE (rem/year)



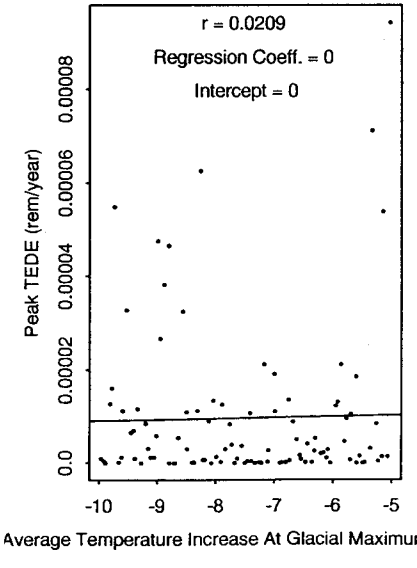
Parameter No. 1



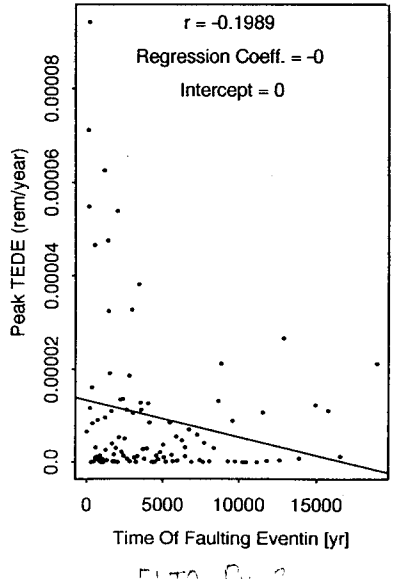
Parameter No. 2



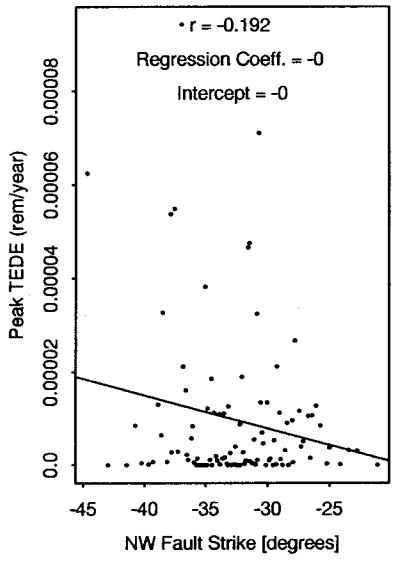
Parameter No. 3



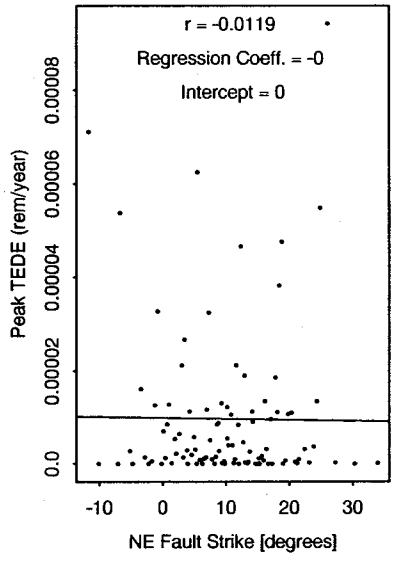
Parameter No. 4



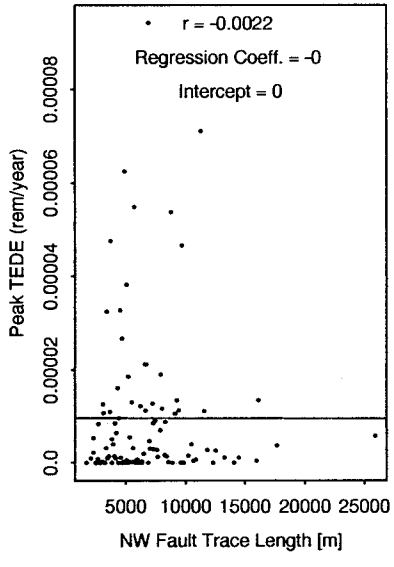
Parameter No. 5



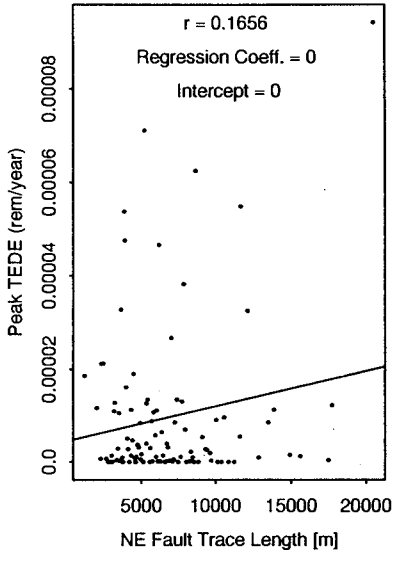
Parameter No. 6



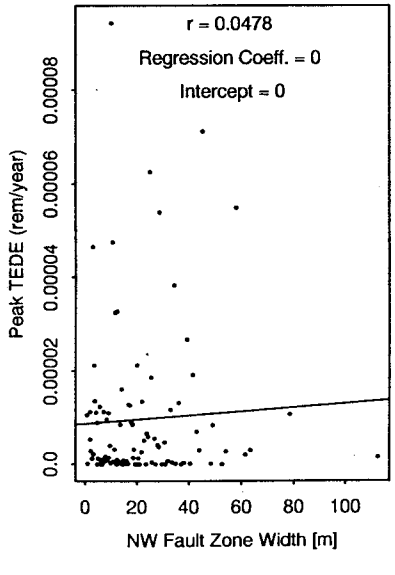
Parameter No. 7



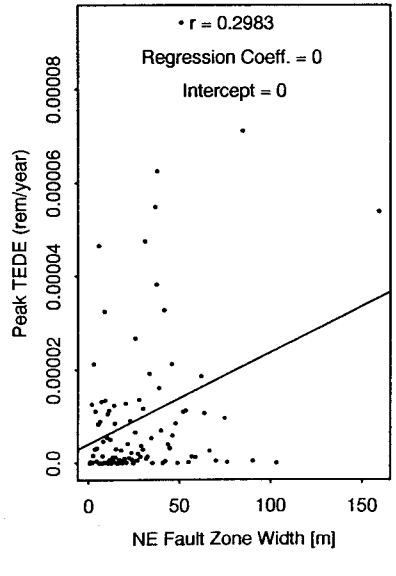
Parameter No. 8



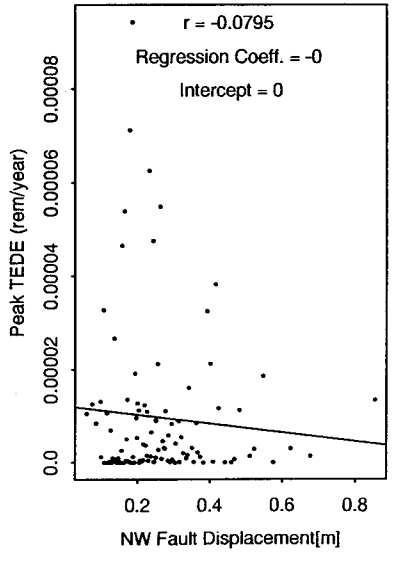
Parameter No. 9



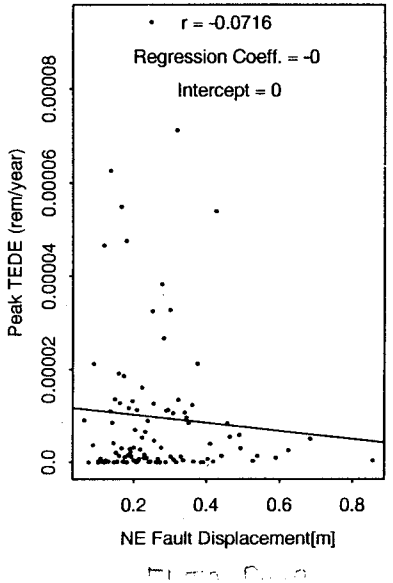
Parameter No. 10



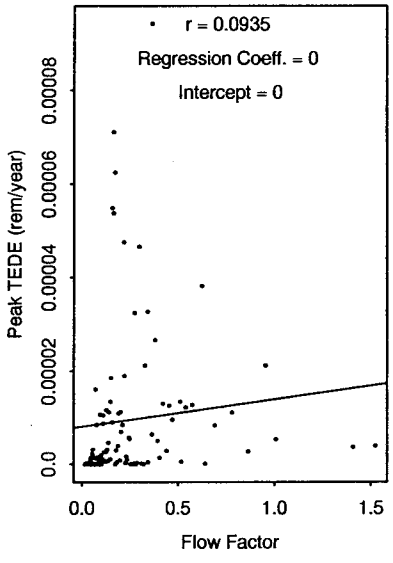
Parameter No. 11



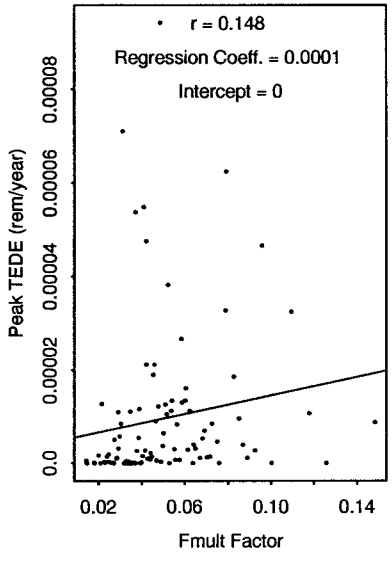
Parameter No. 12



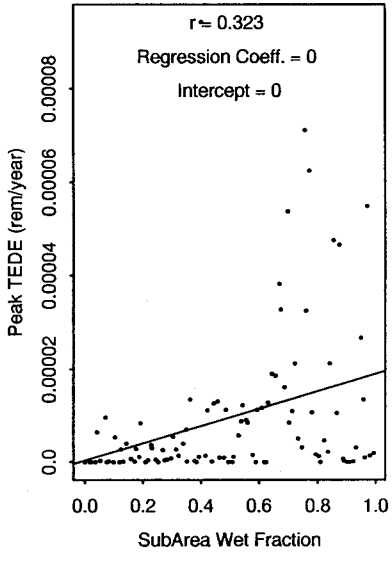
Parameter No. 13



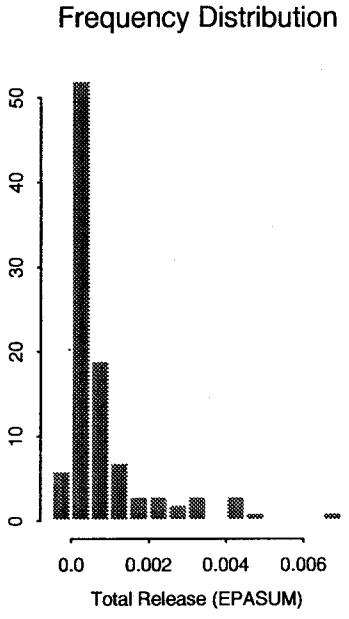
Parameter No. 14

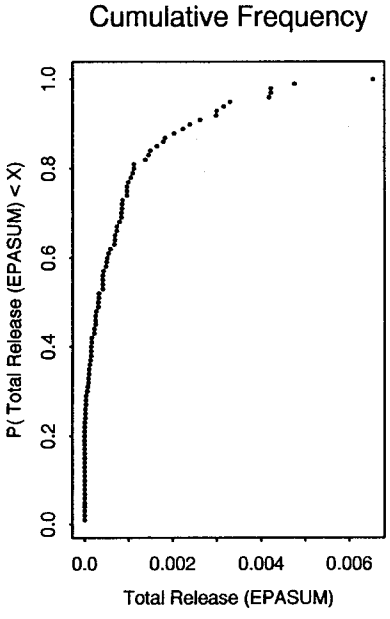


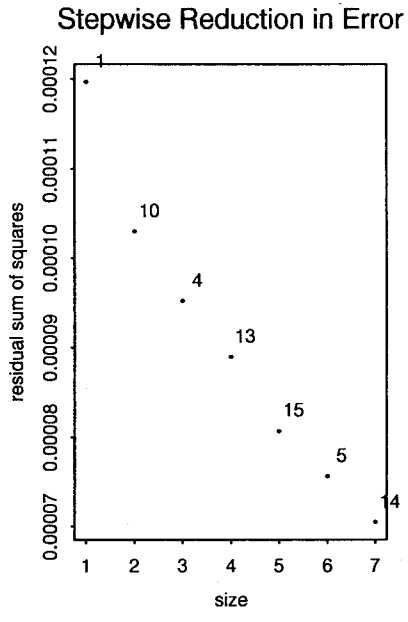
Parameter No. 15

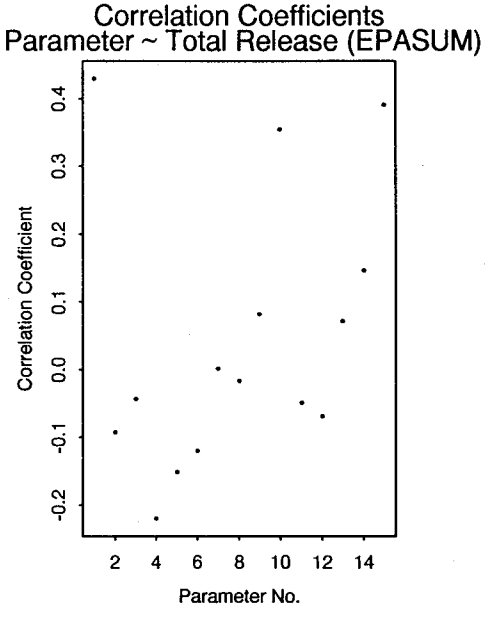


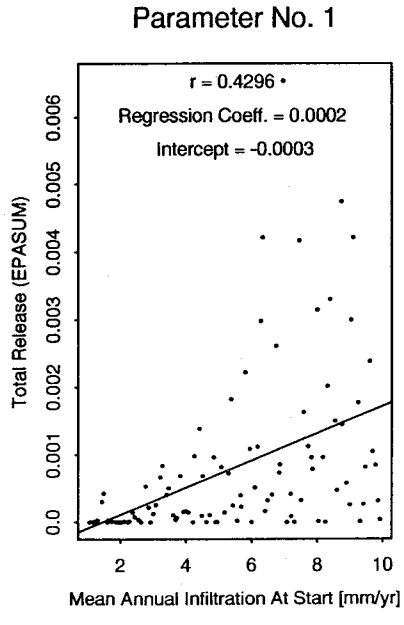
20 km Scenario
Summary Plots for Total Release (EPASUM)

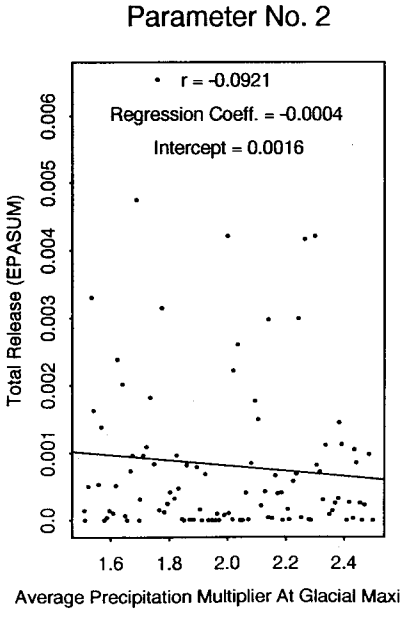


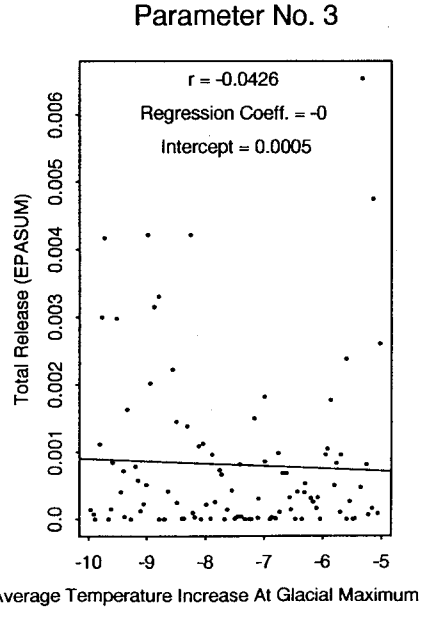


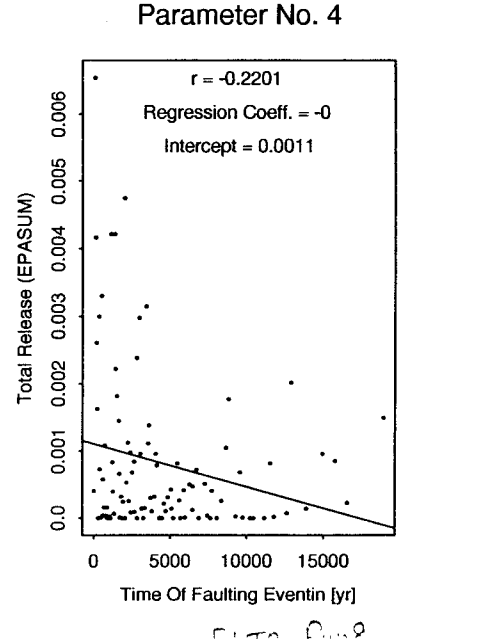


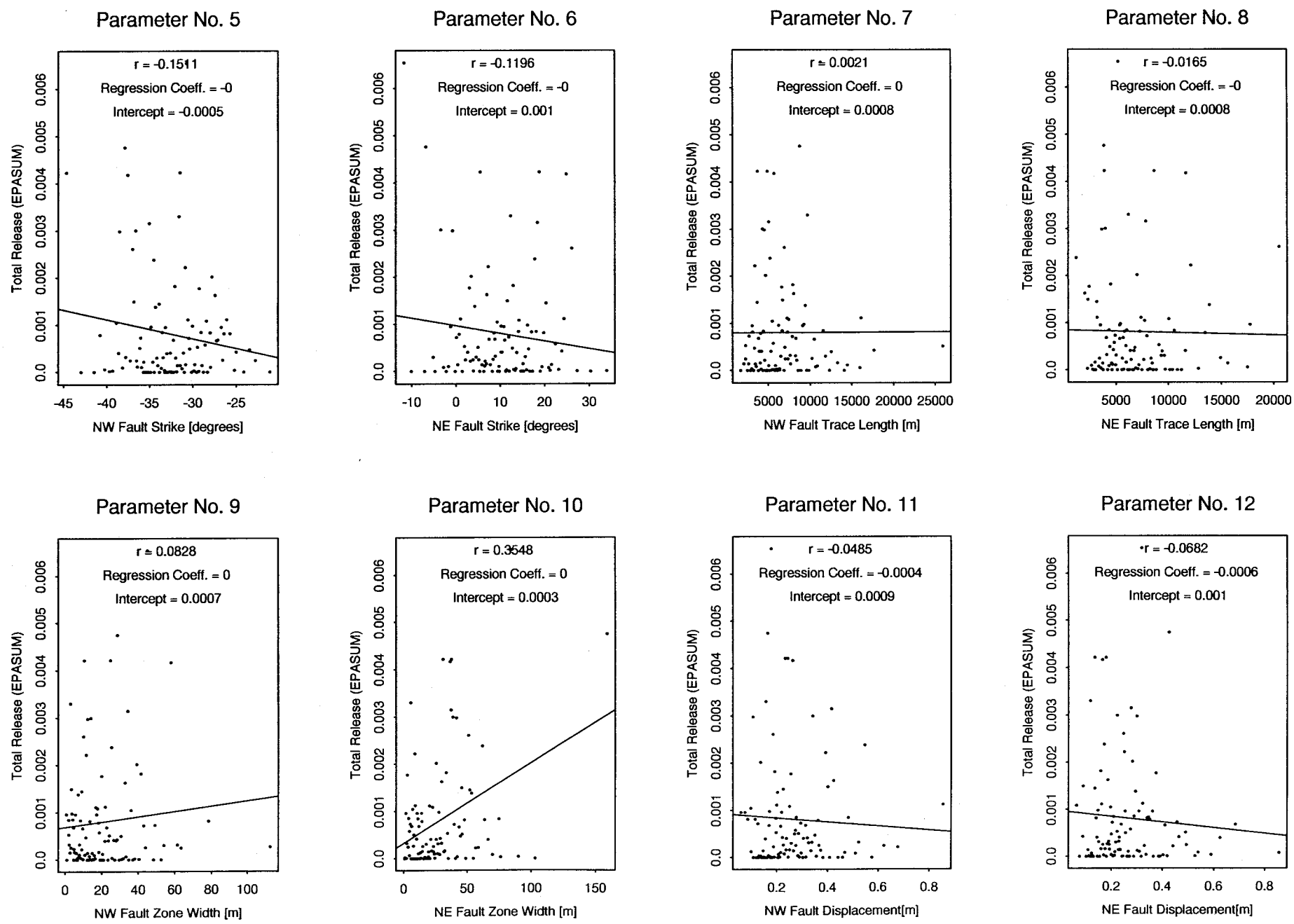








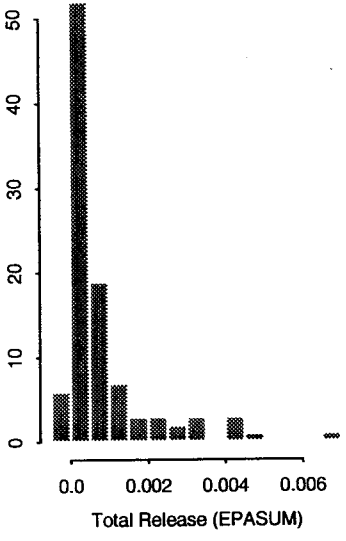



Parameter No. 5
r = -0.1511
Regression Coeff. = -0
Intercept = -0.0005
Total Release (EPASUM)
NW Fault Strike [degrees]
Parameter No. 6
r = -0.1196
Regression Coeff. = -0
Intercept = 0.001
Total Release (EPASUM)
NE Fault Strike [degrees]
Parameter No. 7
r = 0.0021
Regression Coeff. = 0
Intercept = 0.0008
Total Release (EPASUM)
NW Fault Trace Length [m]
Parameter No. 8
r = -0.0165
Regression Coeff. = -0
Intercept = 0.0008
Total Release (EPASUM)
NE Fault Trace Length [m]
Parameter No. 9
r = 0.0828
Regression Coeff. = 0
Intercept = 0.0007
Total Release (EPASUM)
NW Fault Zone Width [m]
Parameter No. 10
r = 0.3548
Regression Coeff. = 0
Intercept = 0.0003
Total Release (EPASUM)
NE Fault Zone Width [m]
Parameter No. 11
r = -0.0485
Regression Coeff. = -0.0004
Intercept = 0.0009
Total Release (EPASUM)
NW Fault Displacement[m]
Parameter No. 12
r = -0.0682
Regression Coeff. = -0.0006
Intercept = 0.001
Total Release (EPASUM)
NE Fault Displacement[m]

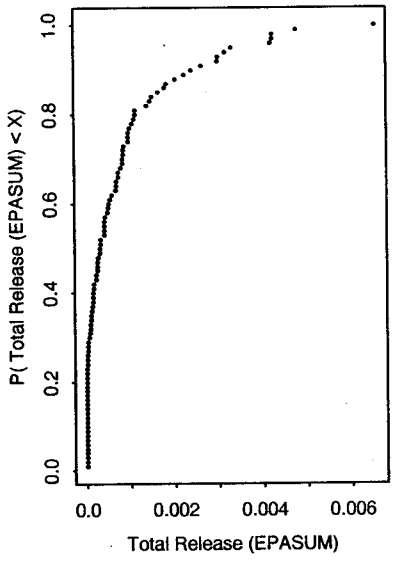
El Tn. Run 8

20 km Scenario
Summary Plots for Total Release (EPASUM)

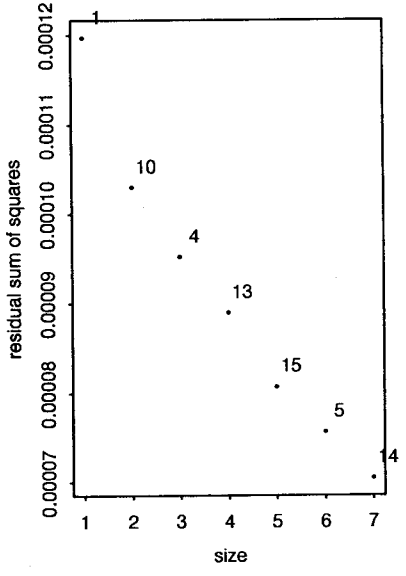
Frequency Distribution



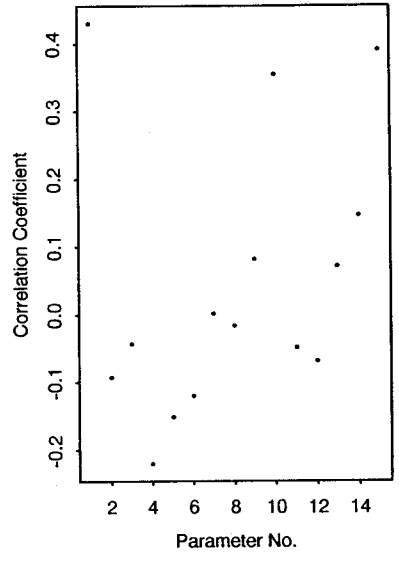
Cumulative Frequency



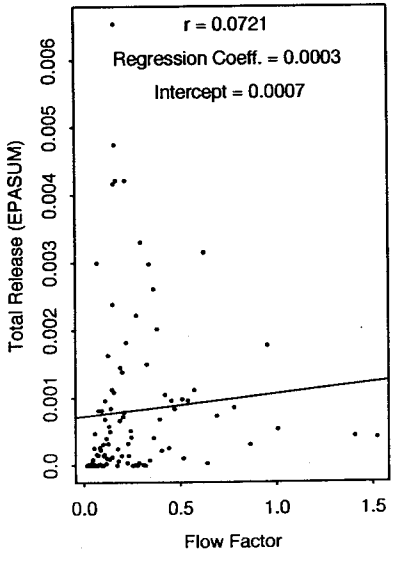
Stepwise Reduction in Error



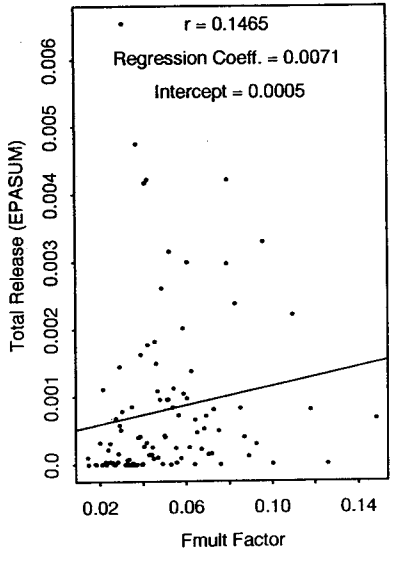
Correlation Coefficients
Parameter ~ Total Release (EPASUM)



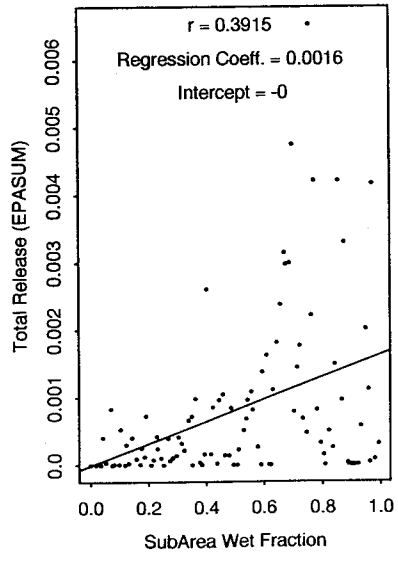
Parameter No. 13



Parameter No. 14

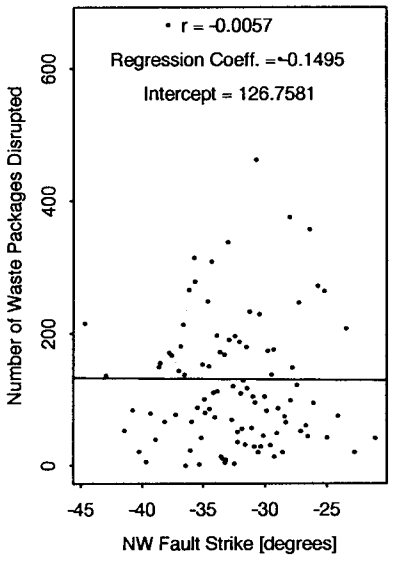


Parameter No. 15

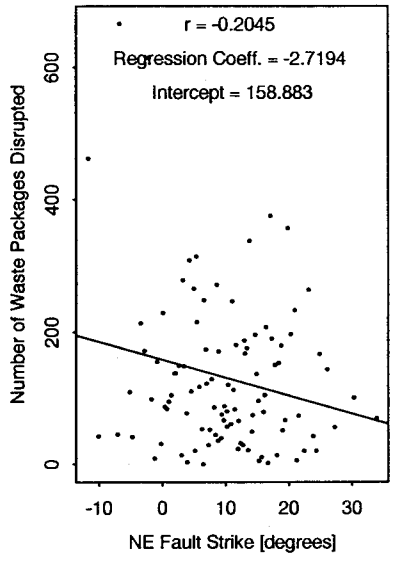


FLTG_Runs

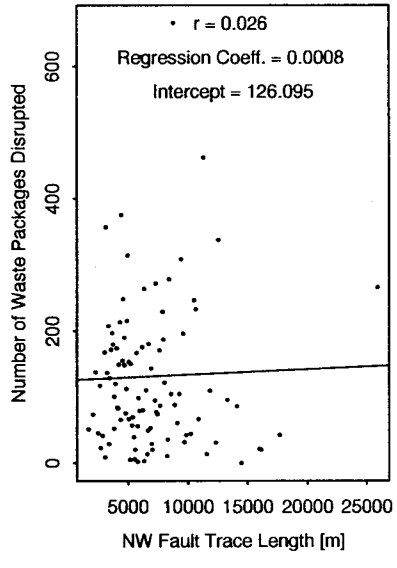
Parameter No. 5



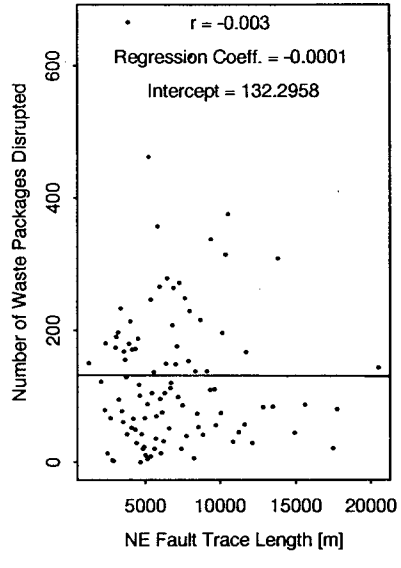
Parameter No. 6



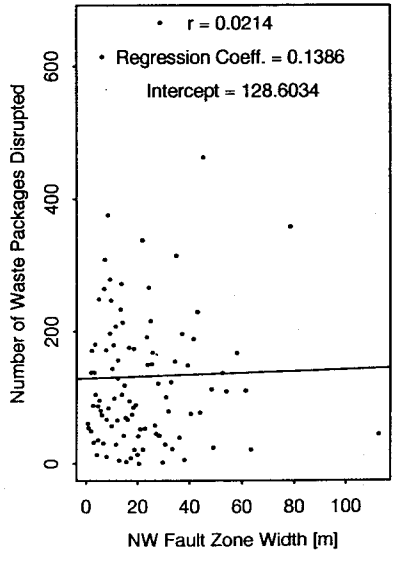
Parameter No. 7



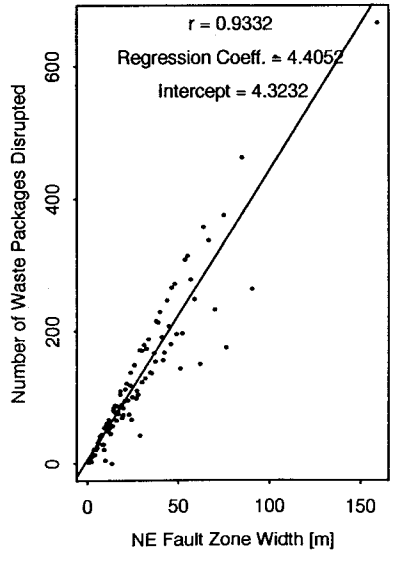
Parameter No. 8



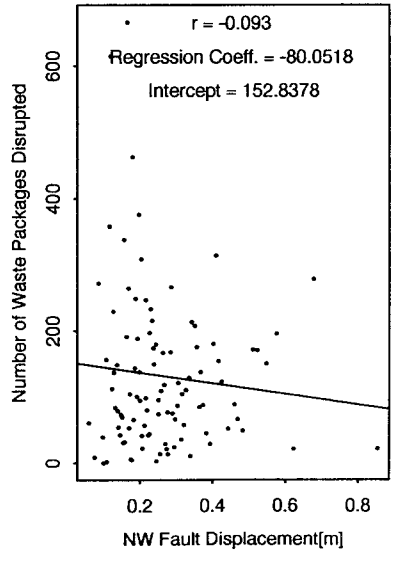
Parameter No. 9



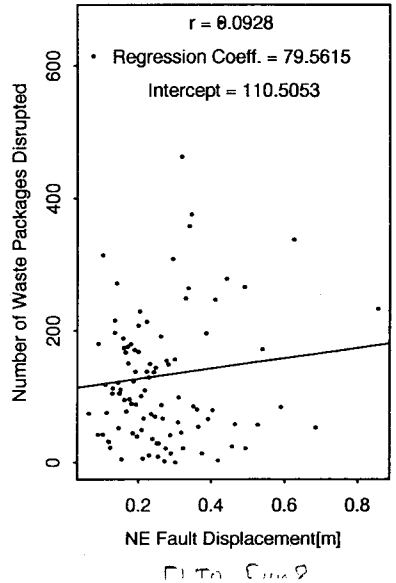
Parameter No. 10

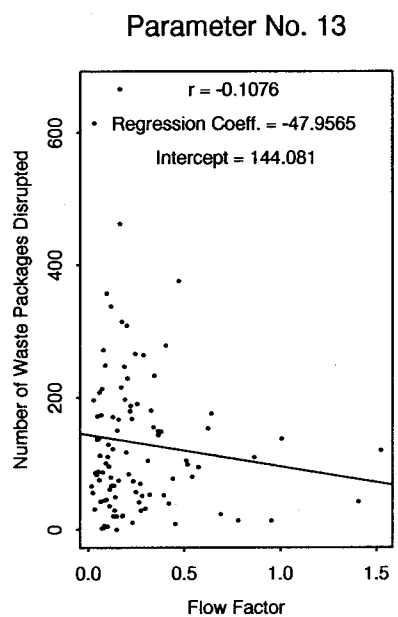


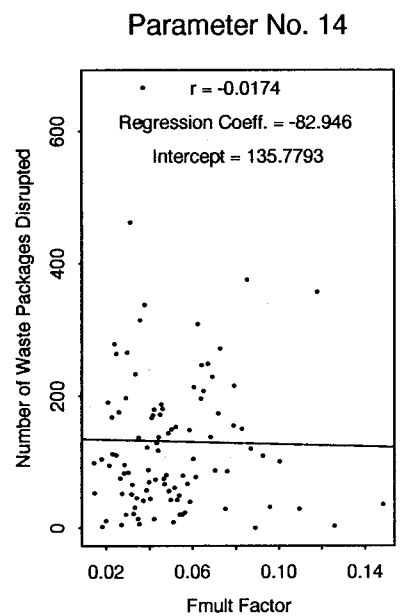
Parameter No. 11

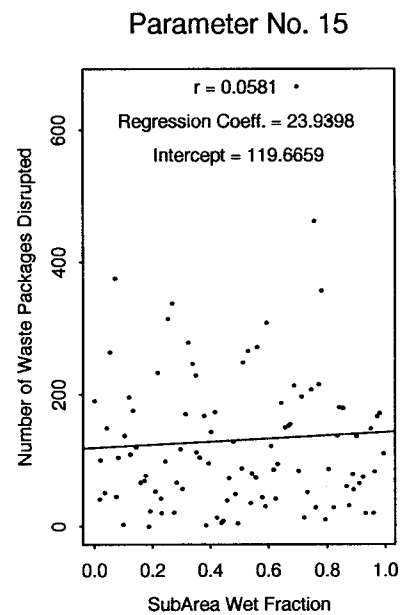


Parameter No. 12




Parameter No. 13
r = -0.1076
Regression Coeff. = -47.9565
Intercept = 144.081
Number of Waste Packages Disrupted
0
200
400
600
0.0
0.5
1.0
1.5
Flow Factor


Parameter No. 14
r = -0.0174
Regression Coeff. = -82.946
Intercept = 135.7793
Number of Waste Packages Disrupted
0
200
400
600
0.02
0.06
0.10
0.14
Fmult Factor


Parameter No. 15
r = 0.0581
Regression Coeff. = 23.9398
Intercept = 119.6659
Number of Waste Packages Disrupted
0
200
400
600
0.0
0.2
0.4
0.6
0.8
1.0
SubArea Wet Fraction

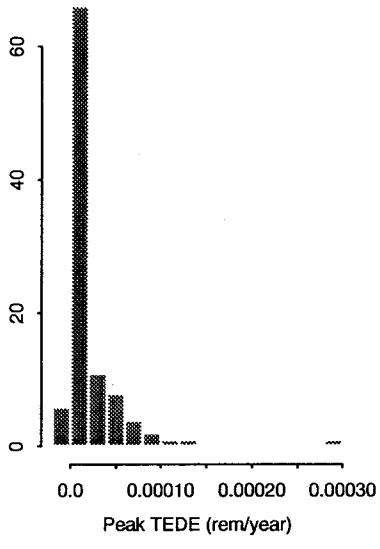
APPENDIX J:

Run: FLTO_Run9

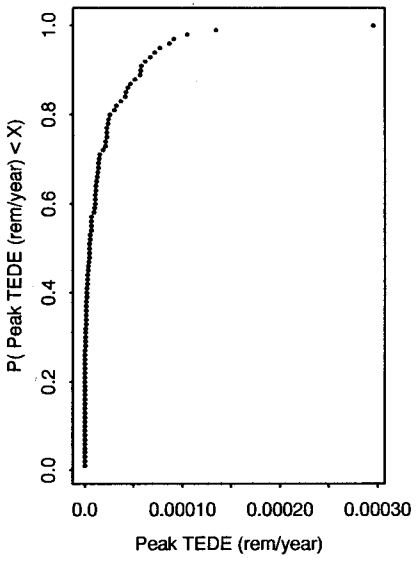
Distance to Focused Group = 20 km
Recurrence Interval = 500 years
Only FAULTO with Diffused Corrosion
With Backfill

20 km Scenario
Summary Plots for Peak TEDE (rem/year)

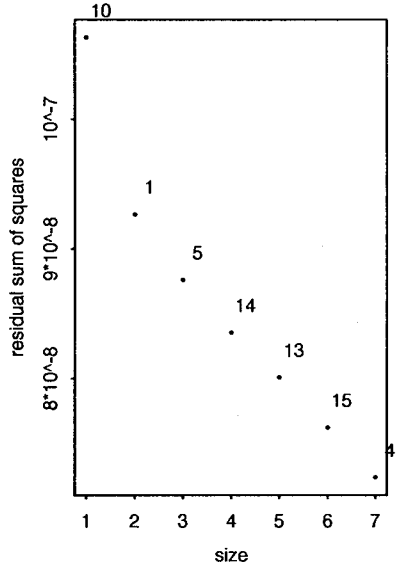
Frequency Distribution



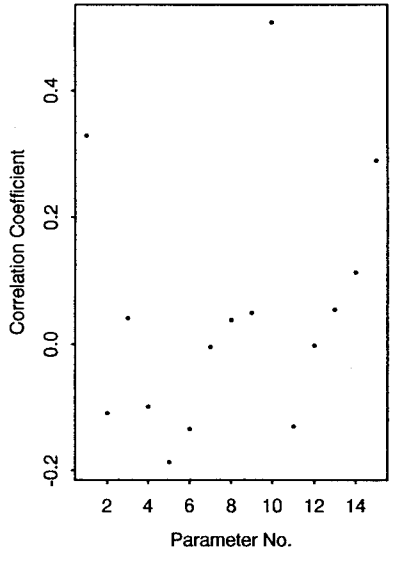
Cumulative Frequency



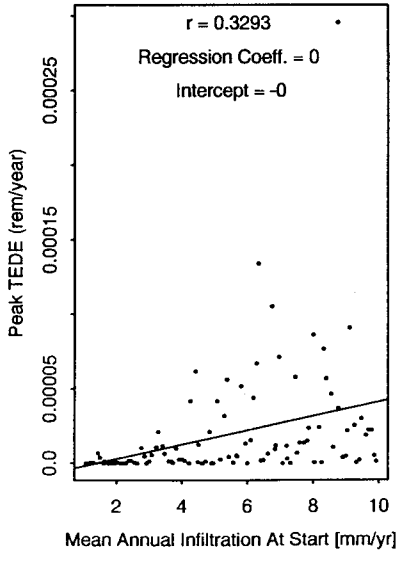
Stepwise Reduction in Error



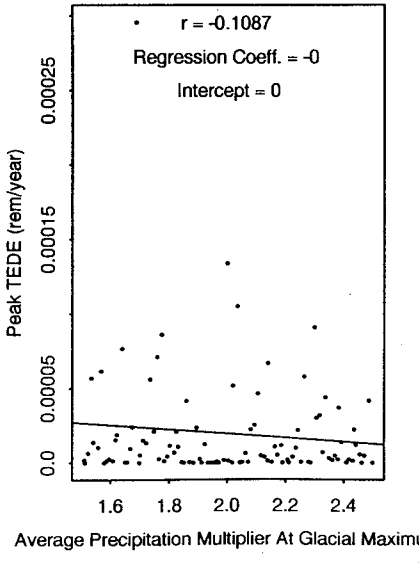
Correlation Coefficients
Parameter ~ Peak TEDE (rem/year)



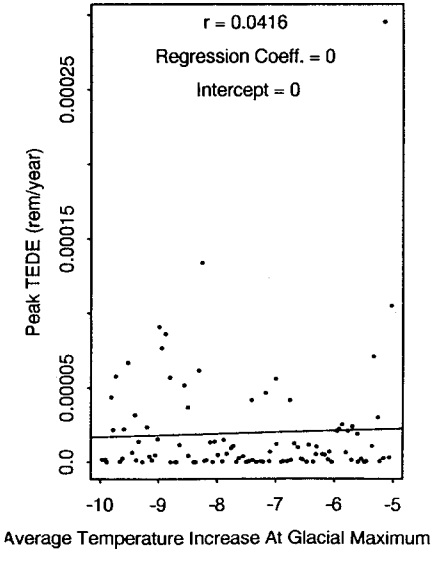
Parameter No. 1



Parameter No. 2



Parameter No. 3



Parameter No. 4

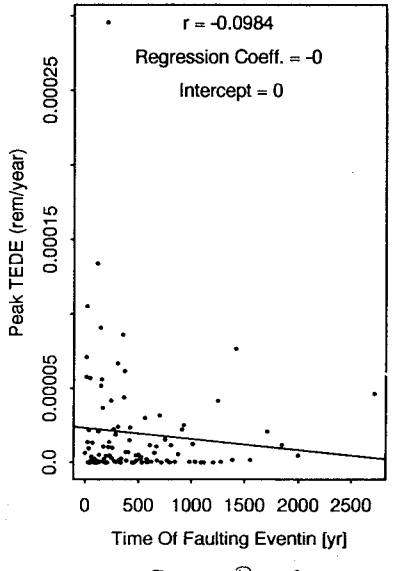
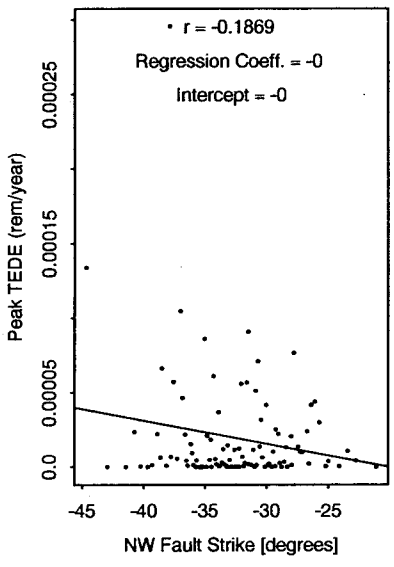
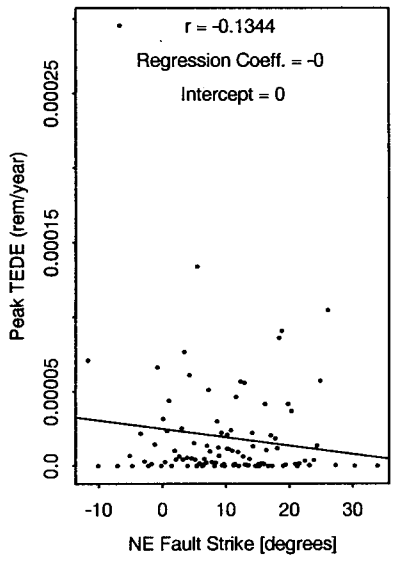


FIG B-1

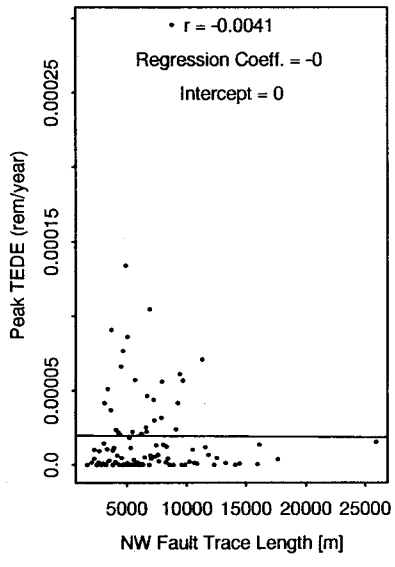
Parameter No. 5



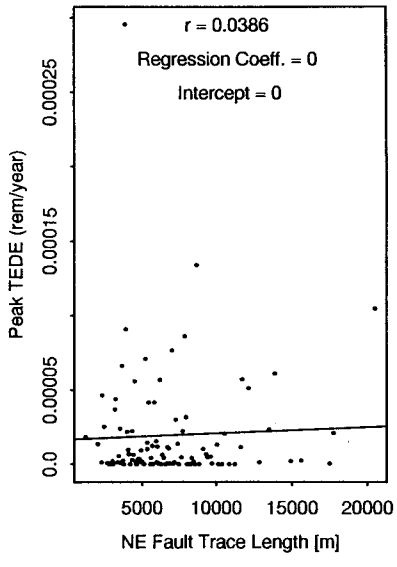
Parameter No. 6



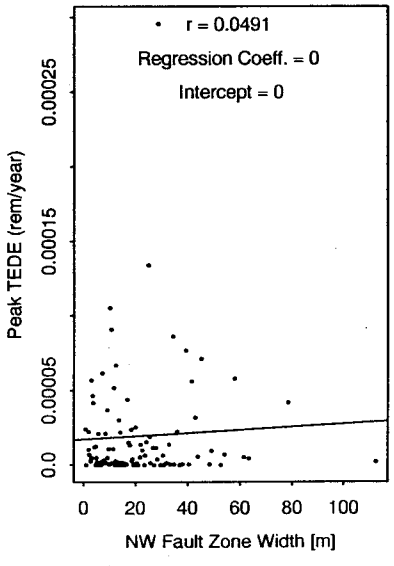
Parameter No. 7



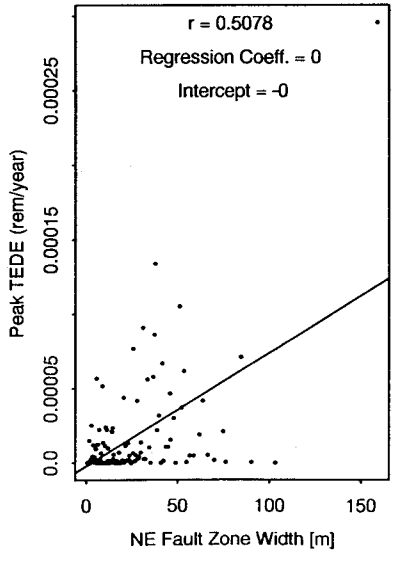
Parameter No. 8



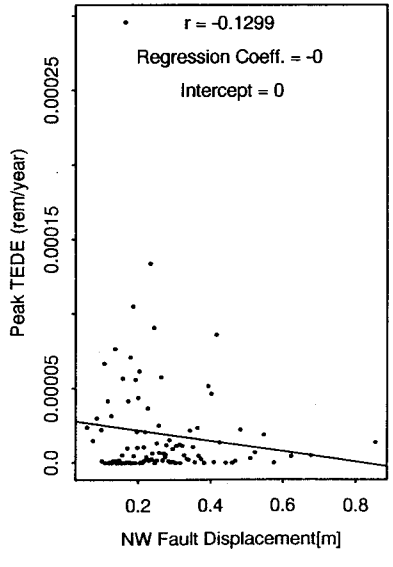
Parameter No. 9



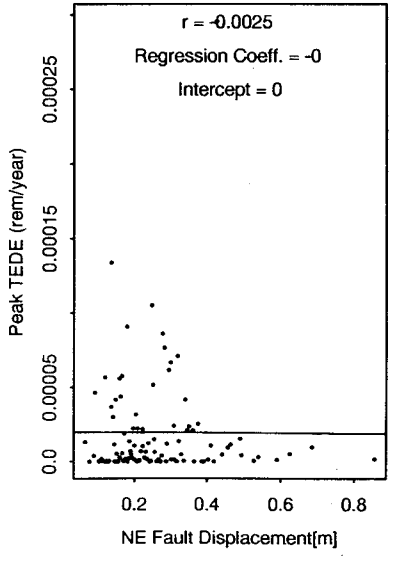
Parameter No. 10

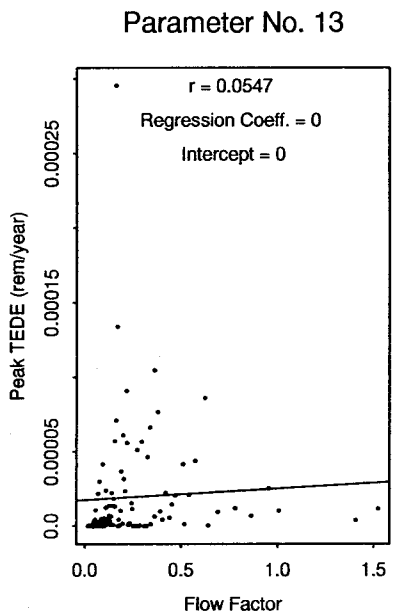


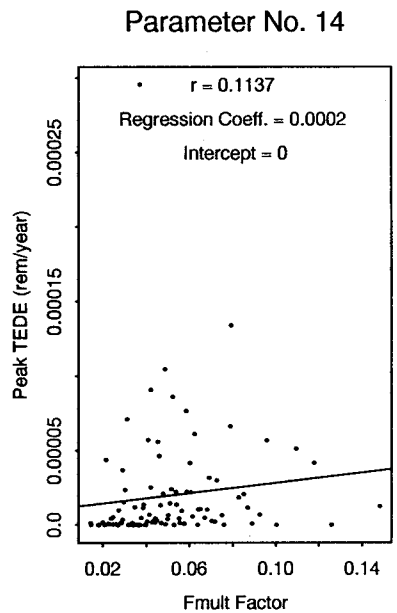
Parameter No. 11

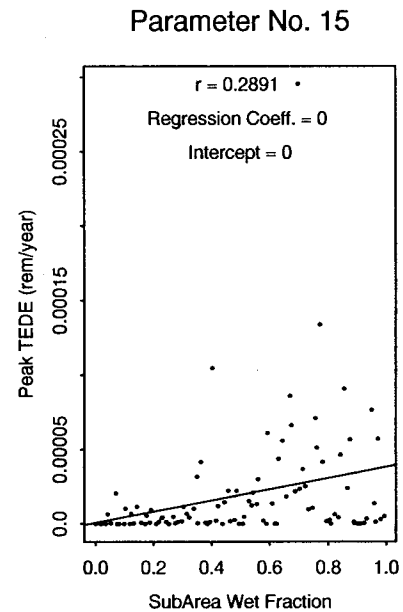


Parameter No. 12



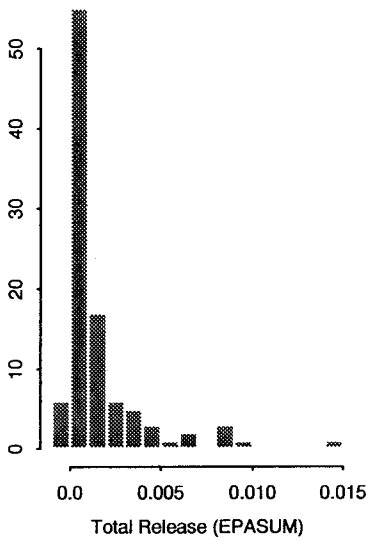

Parameter No. 13
r = 0.0547
Regression Coeff. = 0
Intercept = 0
Peak TEDE (rem/year)
0.0
0.00005
0.00015
0.00025
0.0
0.5
1.0
1.5
Flow Factor


Parameter No. 14
r = 0.1137
Regression Coeff. = 0.0002
Intercept = 0
Peak TEDE (rem/year)
0.0
0.00005
0.00015
0.00025
0.02
0.06
0.10
0.14
Fmult Factor

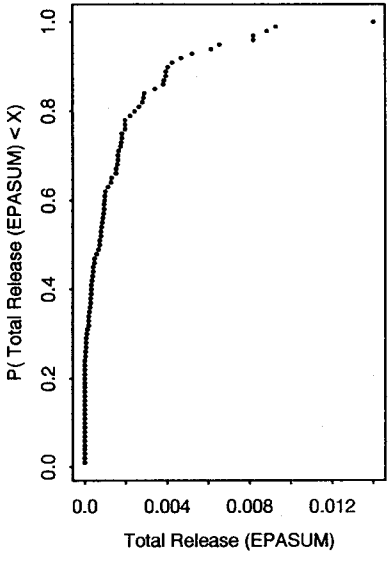

Parameter No. 15
r = 0.2891
Regression Coeff. = 0
Intercept = 0
Peak TEDE (rem/year)
0.0
0.00005
0.00015
0.00025
0.0
0.2
0.4
0.6
0.8
1.0
SubArea Wet Fraction

20 km Scenario
Summary Plots for Total Release (EPASUM)

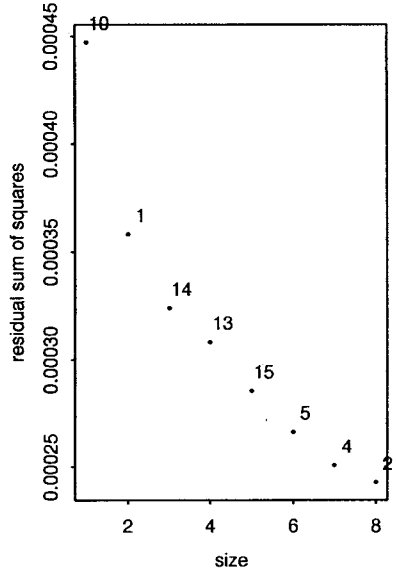
Frequency Distribution



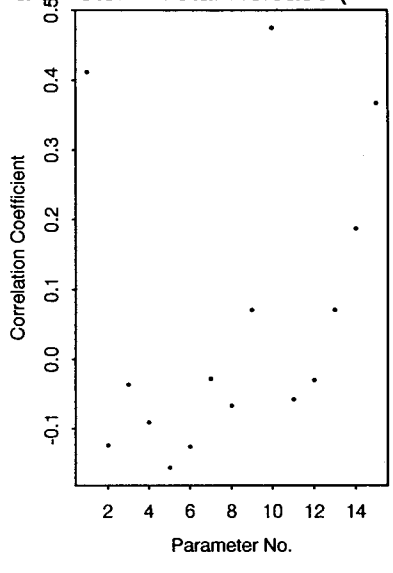
Cumulative Frequency



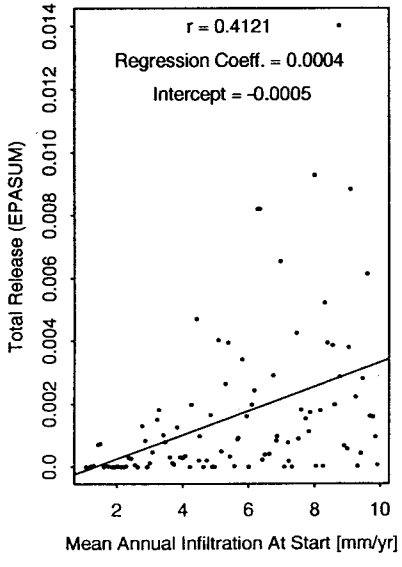
Stepwise Reduction in Error



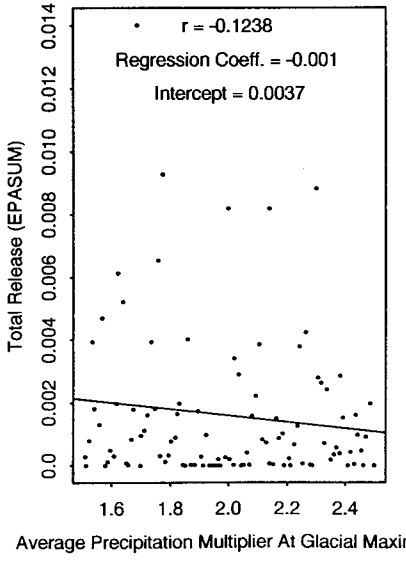
Correlation Coefficients
Parameter ~ Total Release (EPASUM)



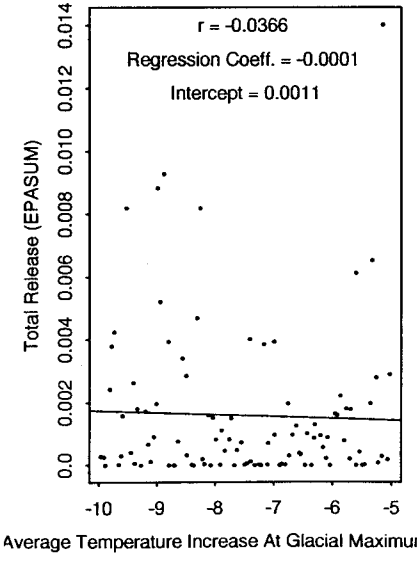
Parameter No. 1



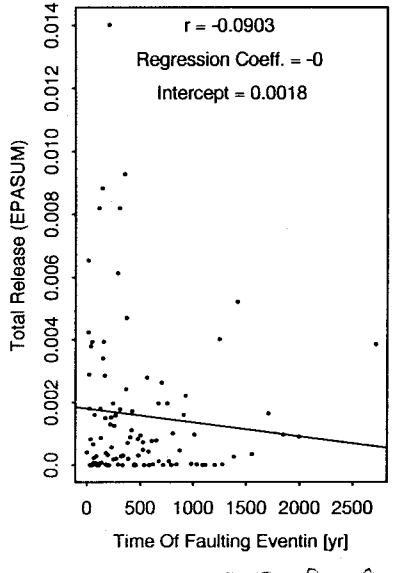
Parameter No. 2



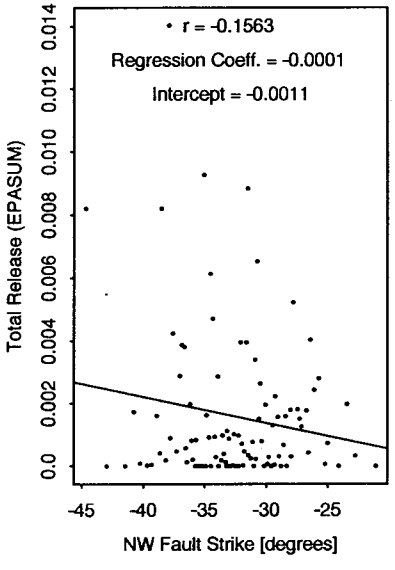
Parameter No. 3



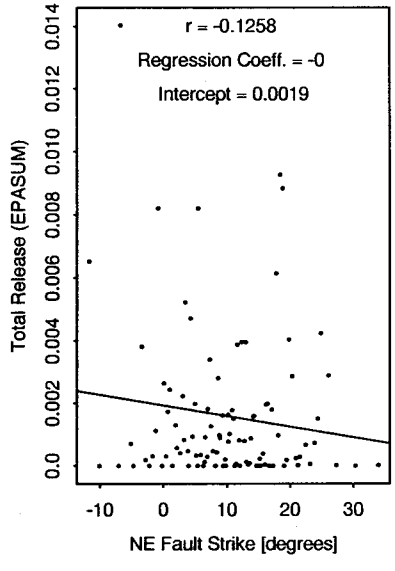
Parameter No. 4



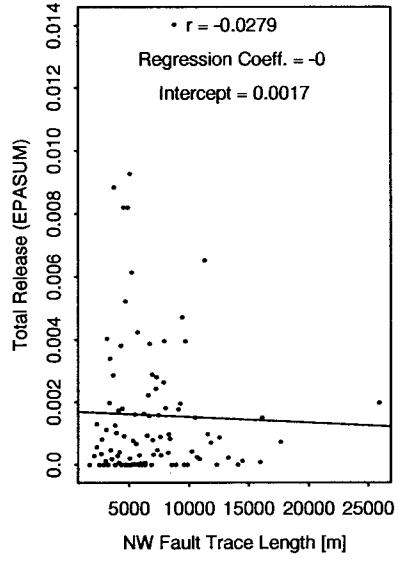
Parameter No. 5



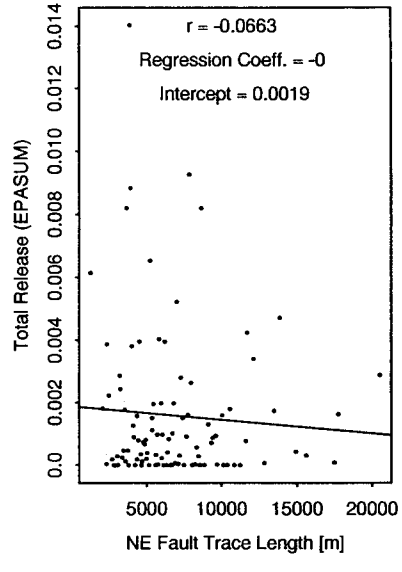
Parameter No. 6



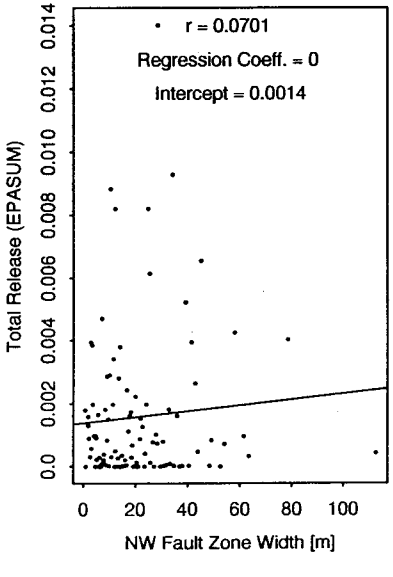
Parameter No. 7



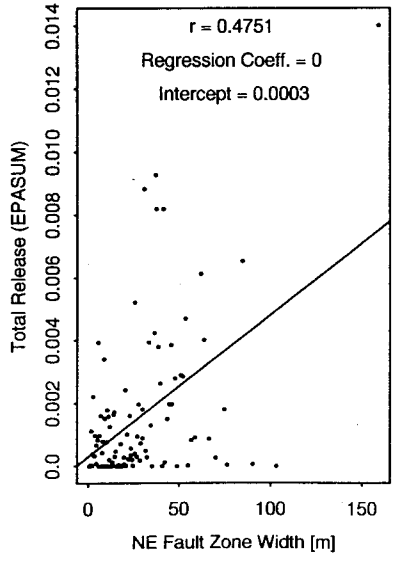
Parameter No. 8



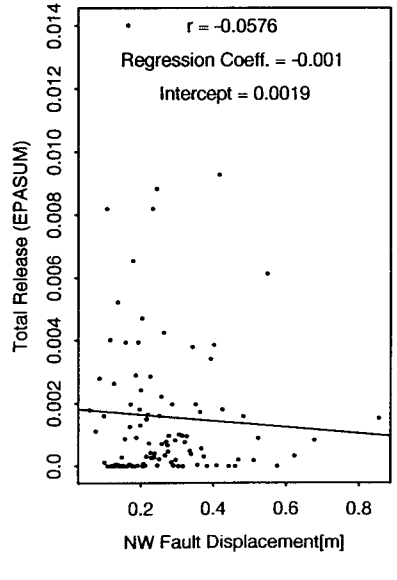
Parameter No. 9



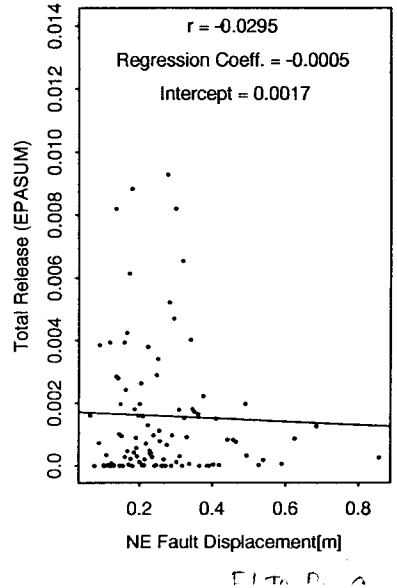
Parameter No. 10



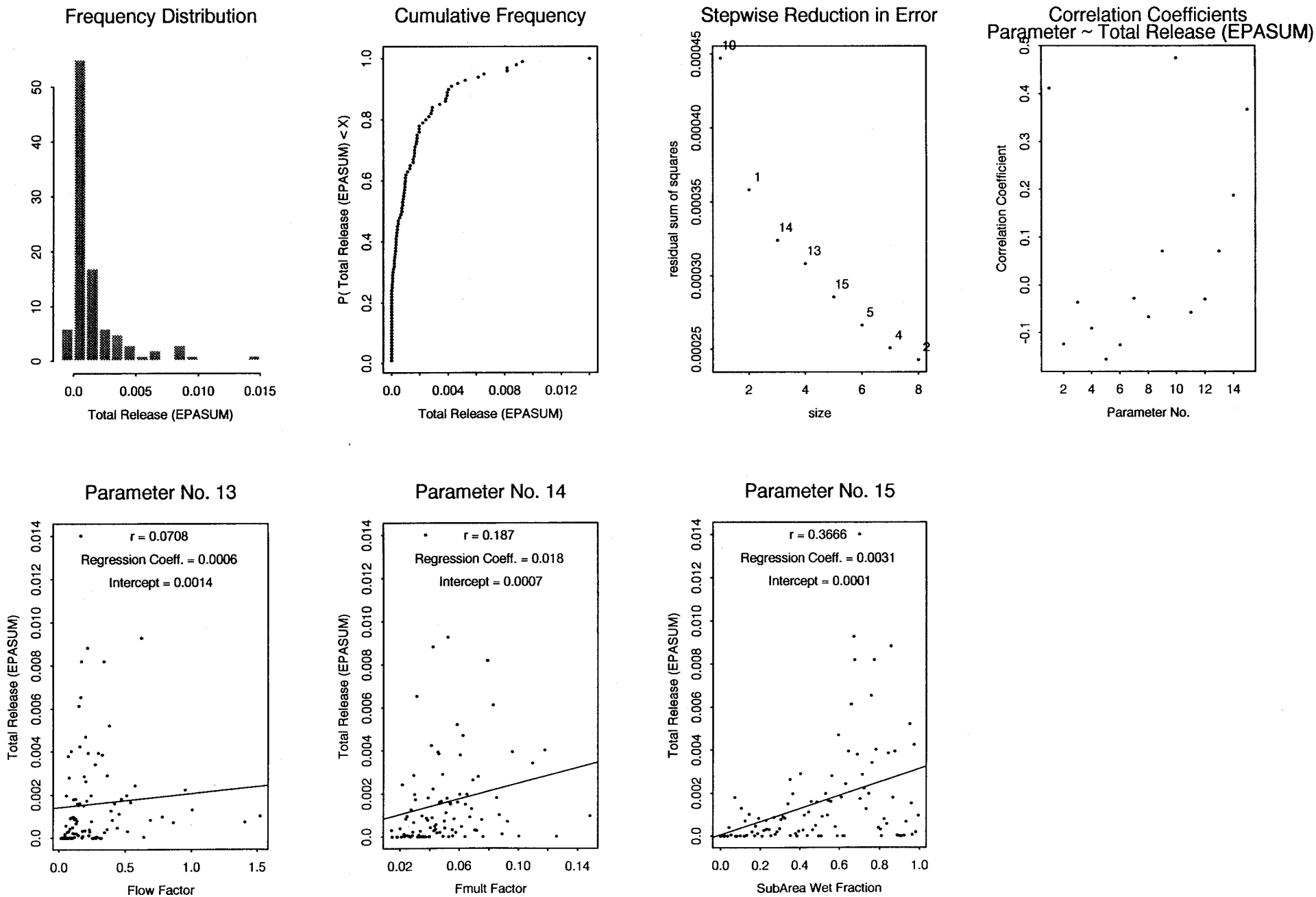
Parameter No. 11



Parameter No. 12

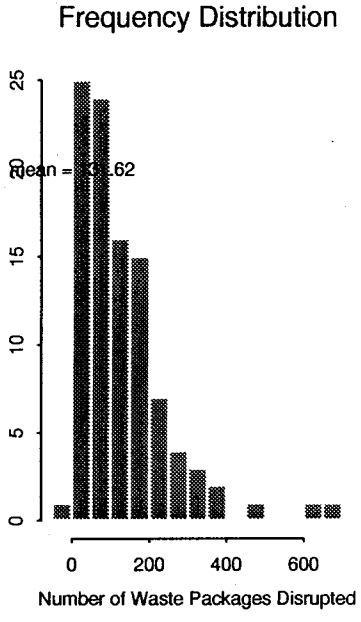


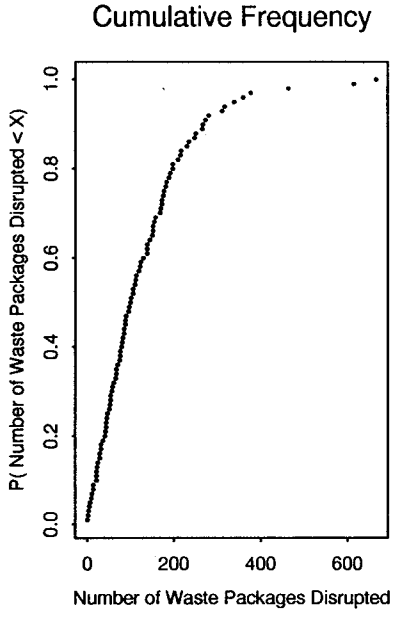
20 km Scenario
Summary Plots for Total Release (EPASUM)

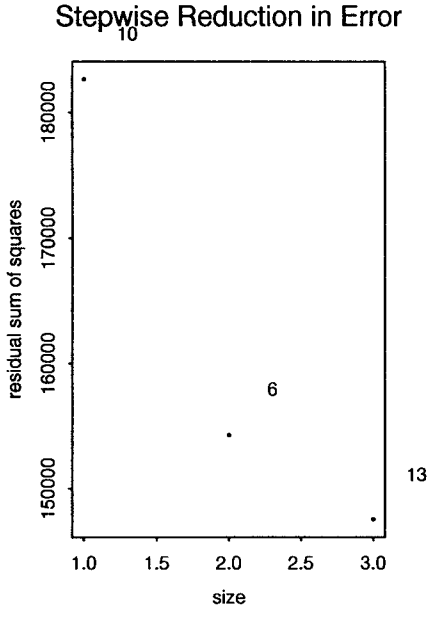


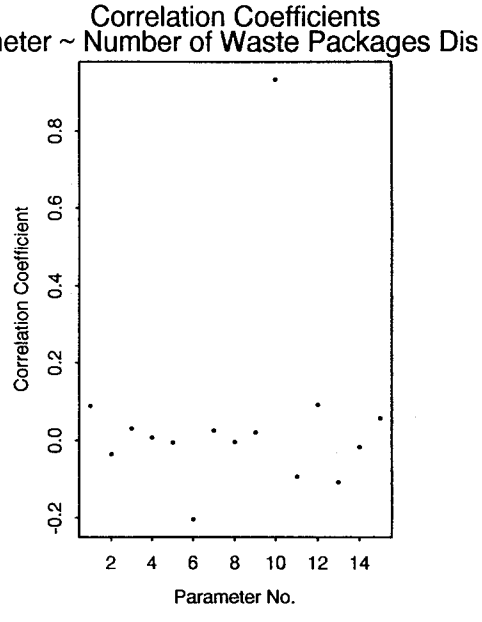
FLTO_Run9

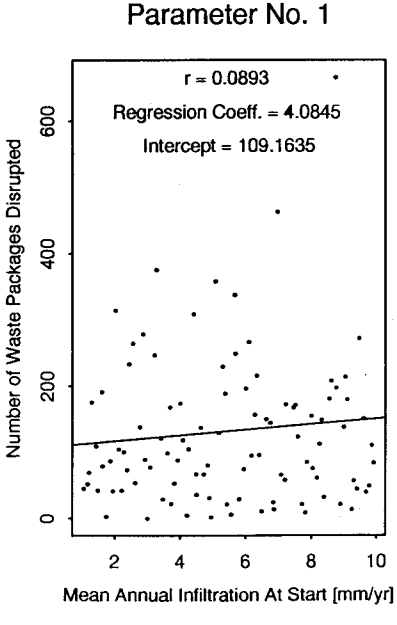
20 km Scenario
Summary Plots for Number of Waste Packages Disrupted

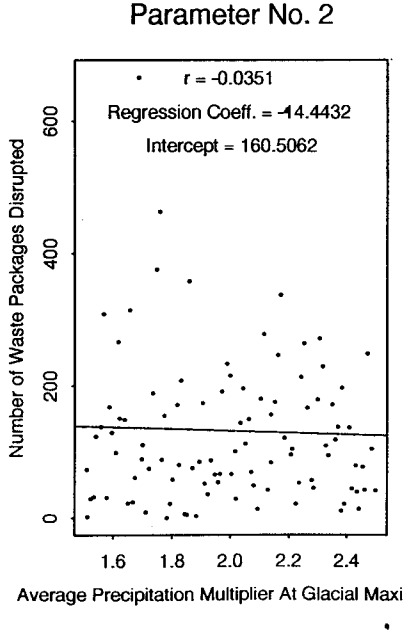


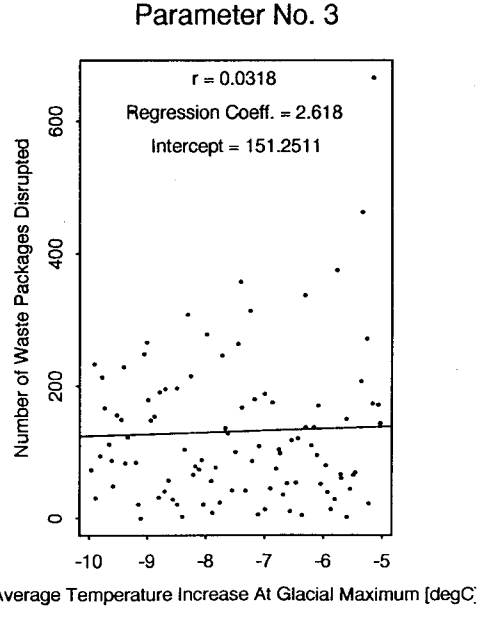


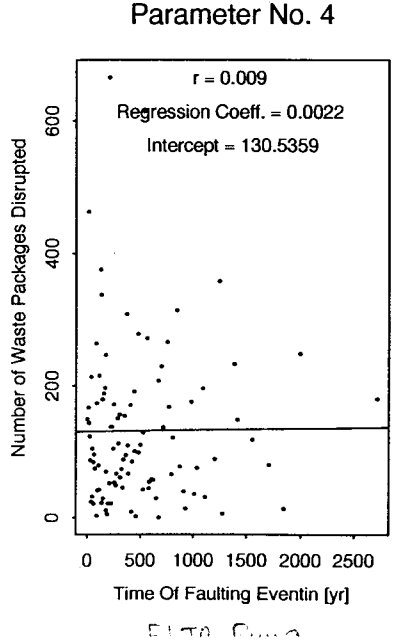




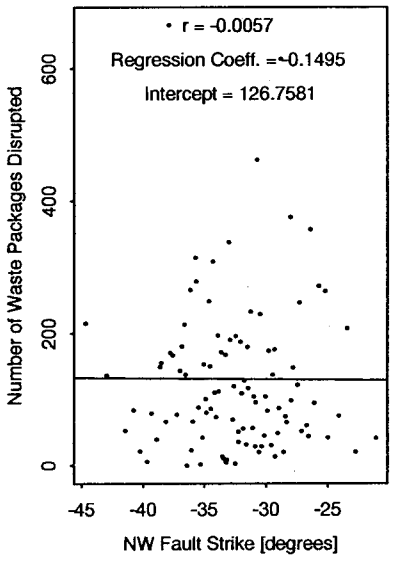




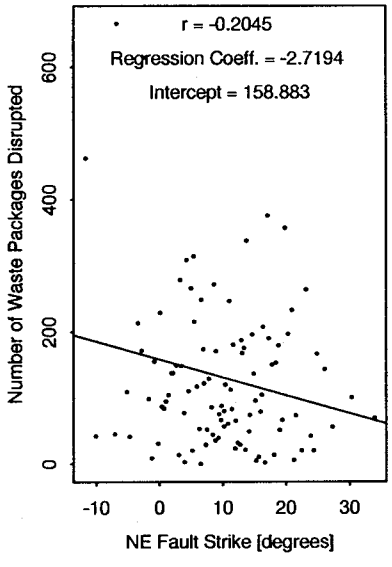




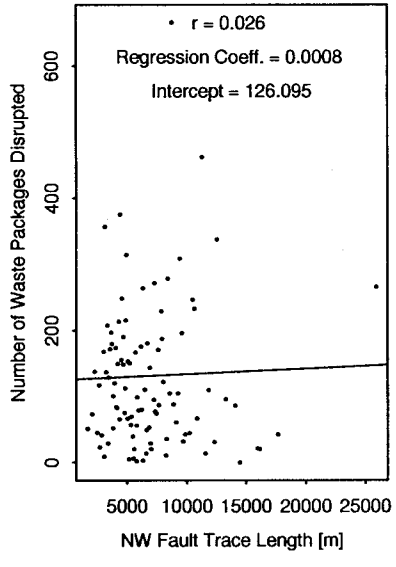
Parameter No. 5



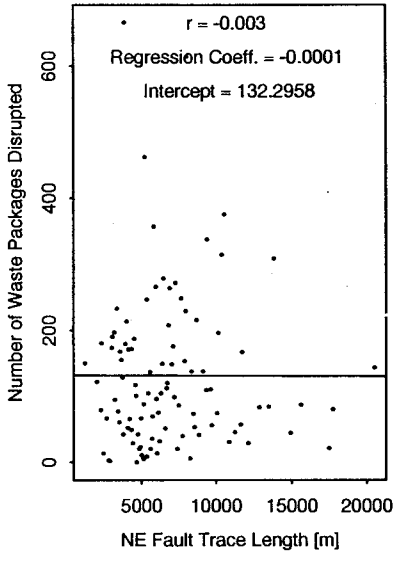
Parameter No. 6



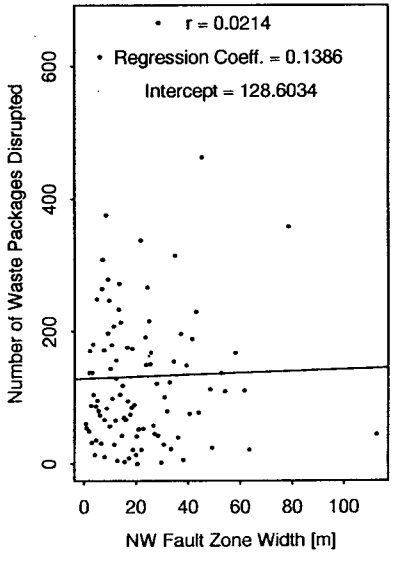
Parameter No. 7



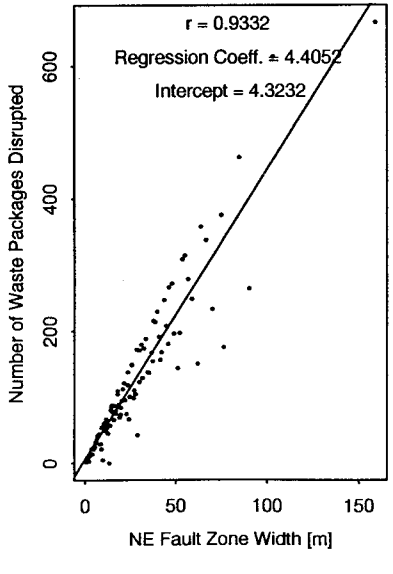
Parameter No. 8



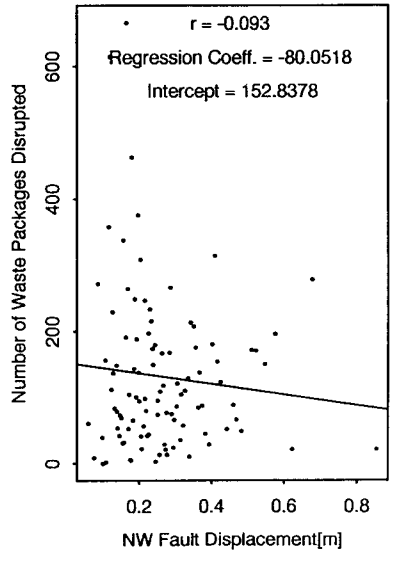
Parameter No. 9



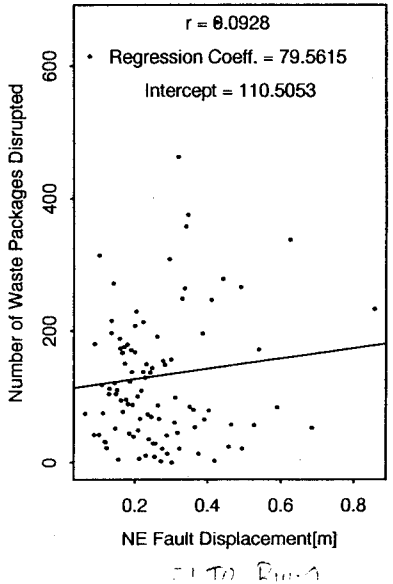
Parameter No. 10



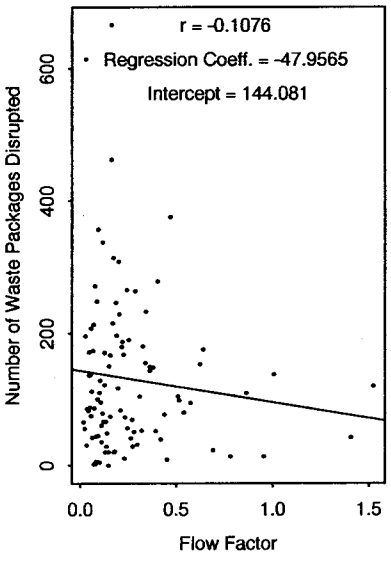
Parameter No. 11



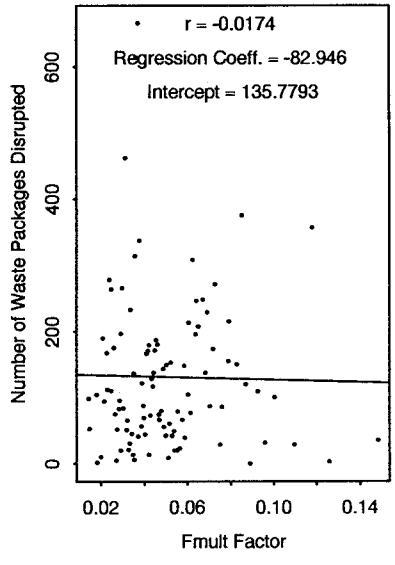
Parameter No. 12



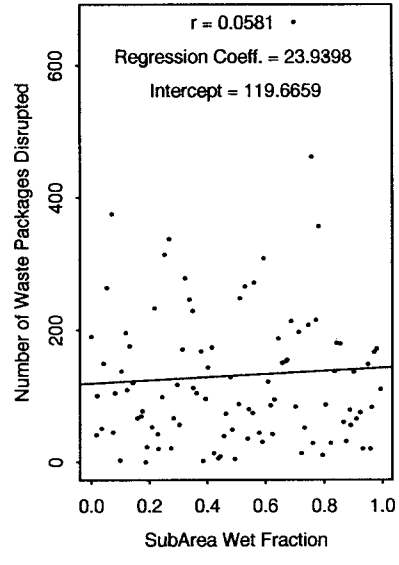
Parameter No. 13



Parameter No. 14



Parameter No. 15

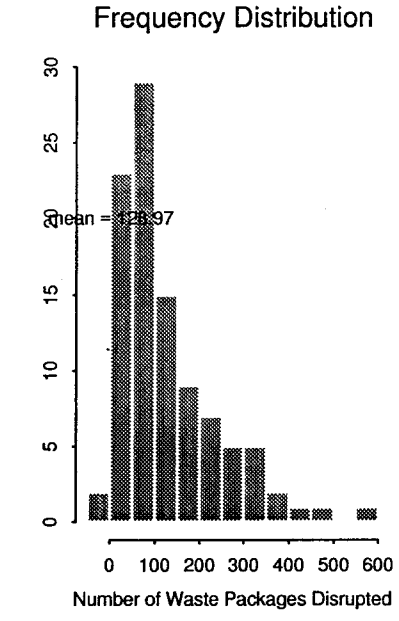


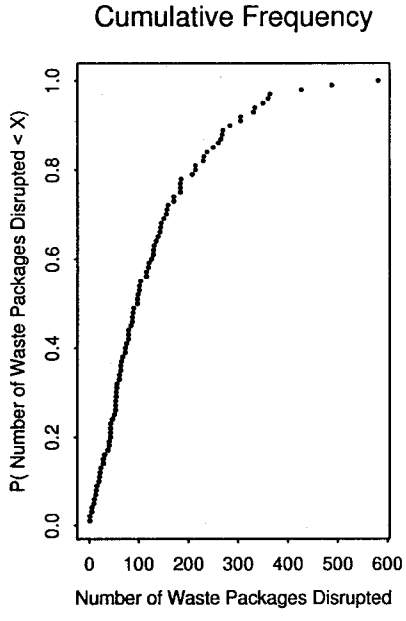
APPENDIX K:

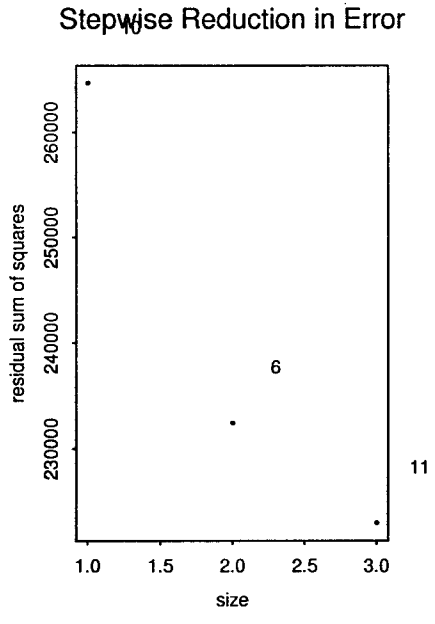
Run: FLTO_Run10

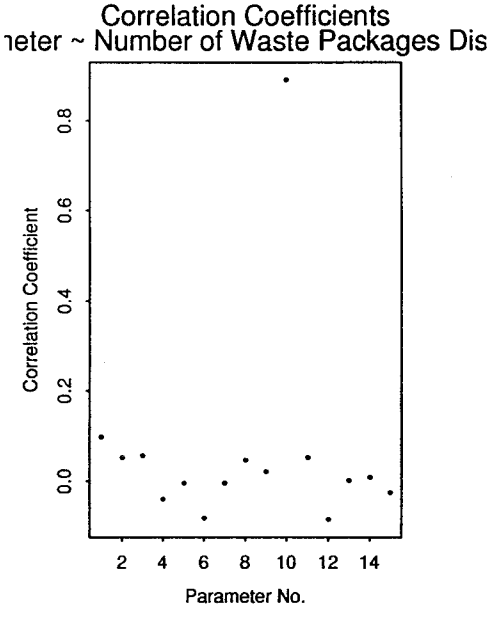
Distance to Focused Group = 5 km
Recurrence Interval = 5,000 years
Only FAULTO with Diffused Corrosion
Without Backfill

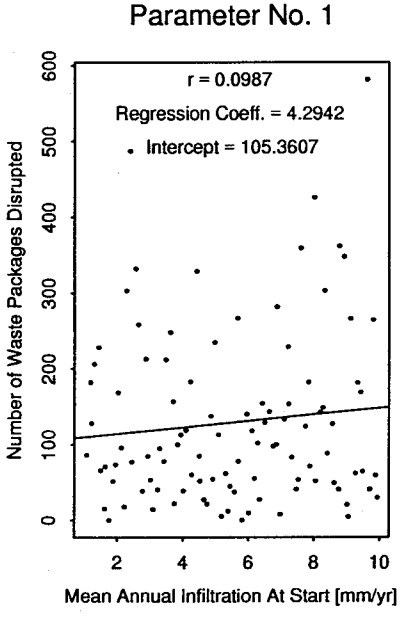
5 km Scenario
Summary Plots for Number of Waste Packages Disrupted

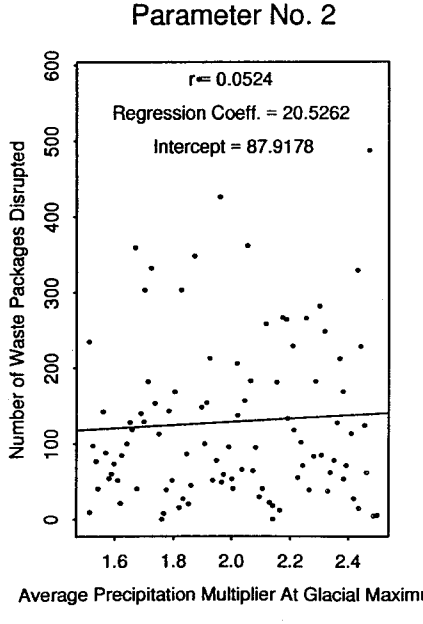


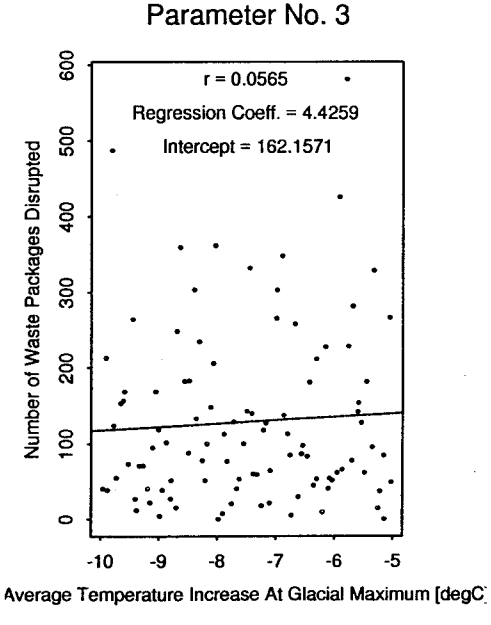


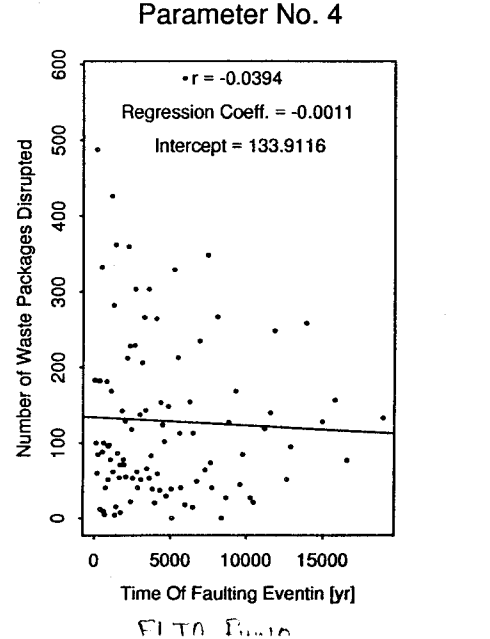


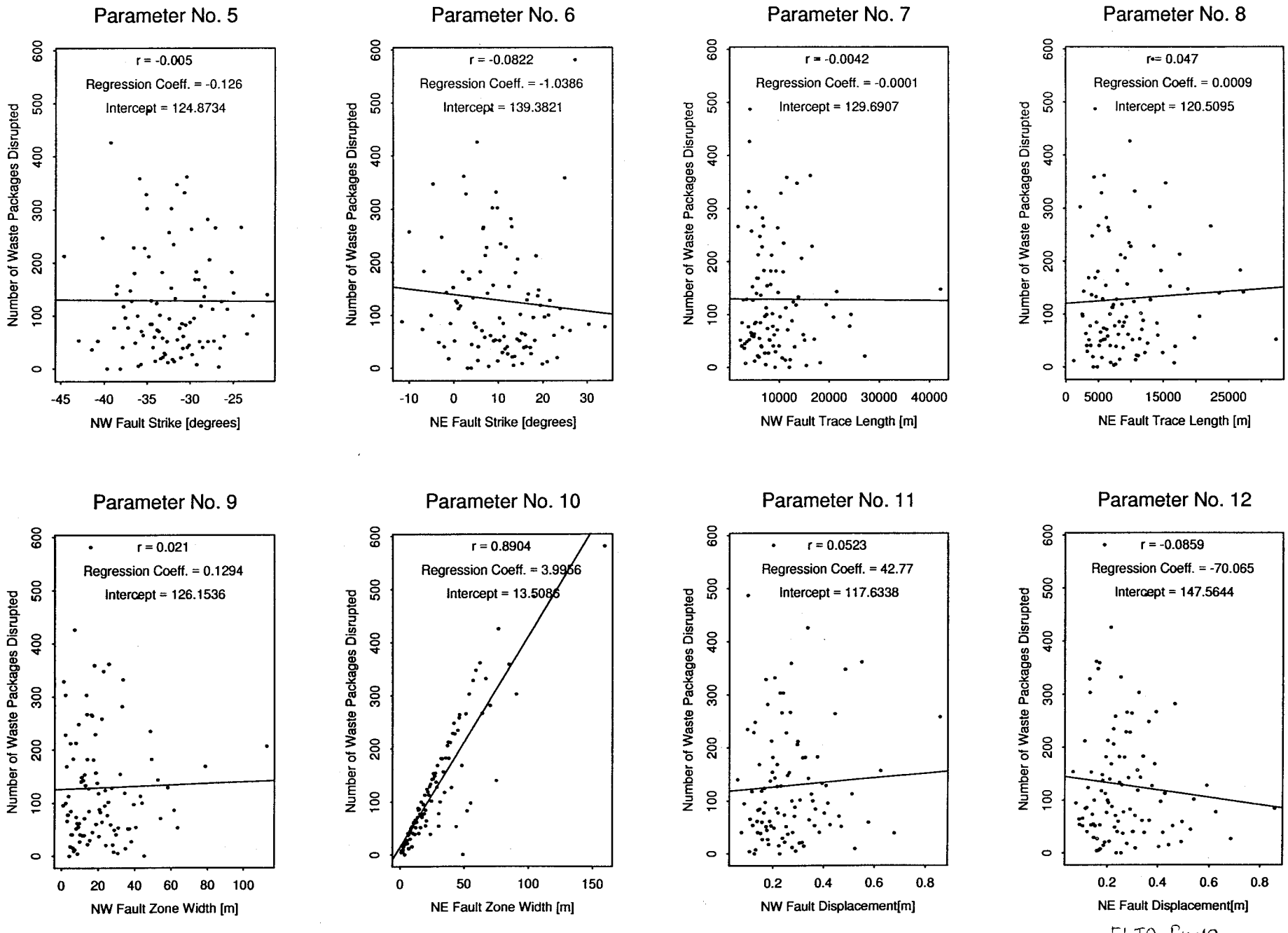




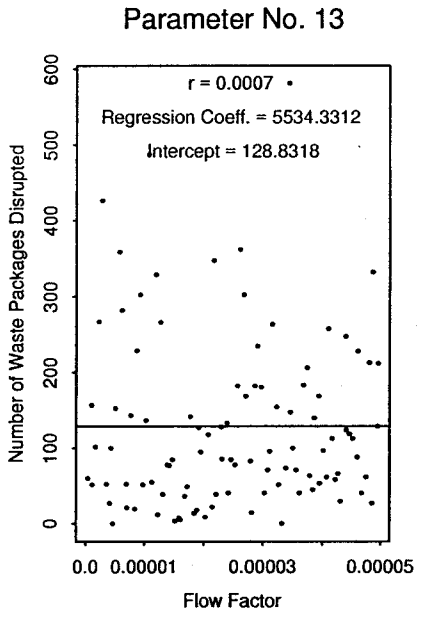


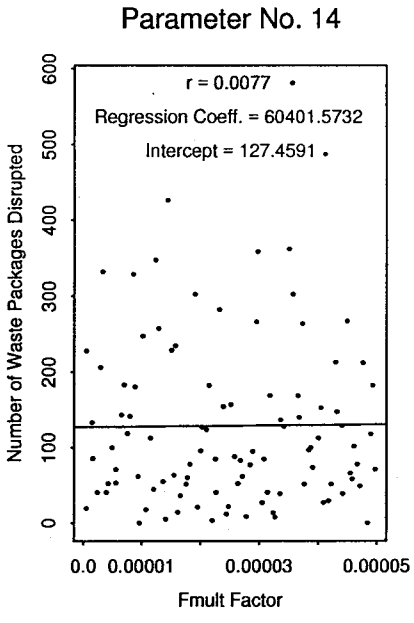


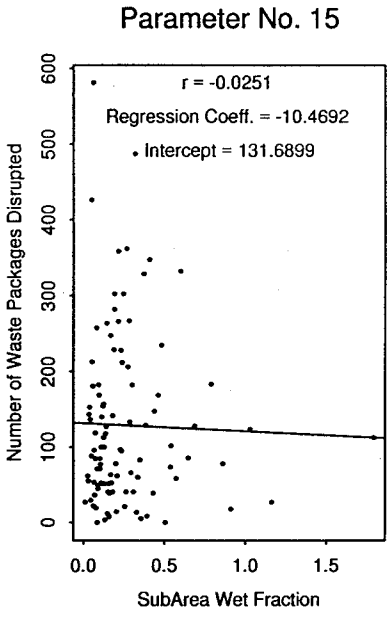



Parameter No. 5
r = -0.005
Regression Coeff. = -0.126
Intercept = 124.8734
Number of Waste Packages Disrupted
NW Fault Strike [degrees]
Parameter No. 6
r = -0.0822
Regression Coeff. = -1.0386
Intercept = 139.3821
Number of Waste Packages Disrupted
NE Fault Strike [degrees]
Parameter No. 7
r = -0.0042
Regression Coeff. = -0.0001
Intercept = 129.6907
Number of Waste Packages Disrupted
NW Fault Trace Length [m]
Parameter No. 8
r = 0.047
Regression Coeff. = 0.0009
Intercept = 120.5095
Number of Waste Packages Disrupted
NE Fault Trace Length [m]
Parameter No. 9
r = 0.021
Regression Coeff. = 0.1294
Intercept = 126.1536
Number of Waste Packages Disrupted
NW Fault Zone Width [m]
Parameter No. 10
r = 0.8904
Regression Coeff. = 3.9956
Intercept = 13.5086
Number of Waste Packages Disrupted
NE Fault Zone Width [m]
Parameter No. 11
r = 0.0523
Regression Coeff. = 42.77
Intercept = 117.6338
Number of Waste Packages Disrupted
NW Fault Displacement[m]
Parameter No. 12
r = -0.0859
Regression Coeff. = -70.065
Intercept = 147.5644
Number of Waste Packages Disrupted
NE Fault Displacement[m]

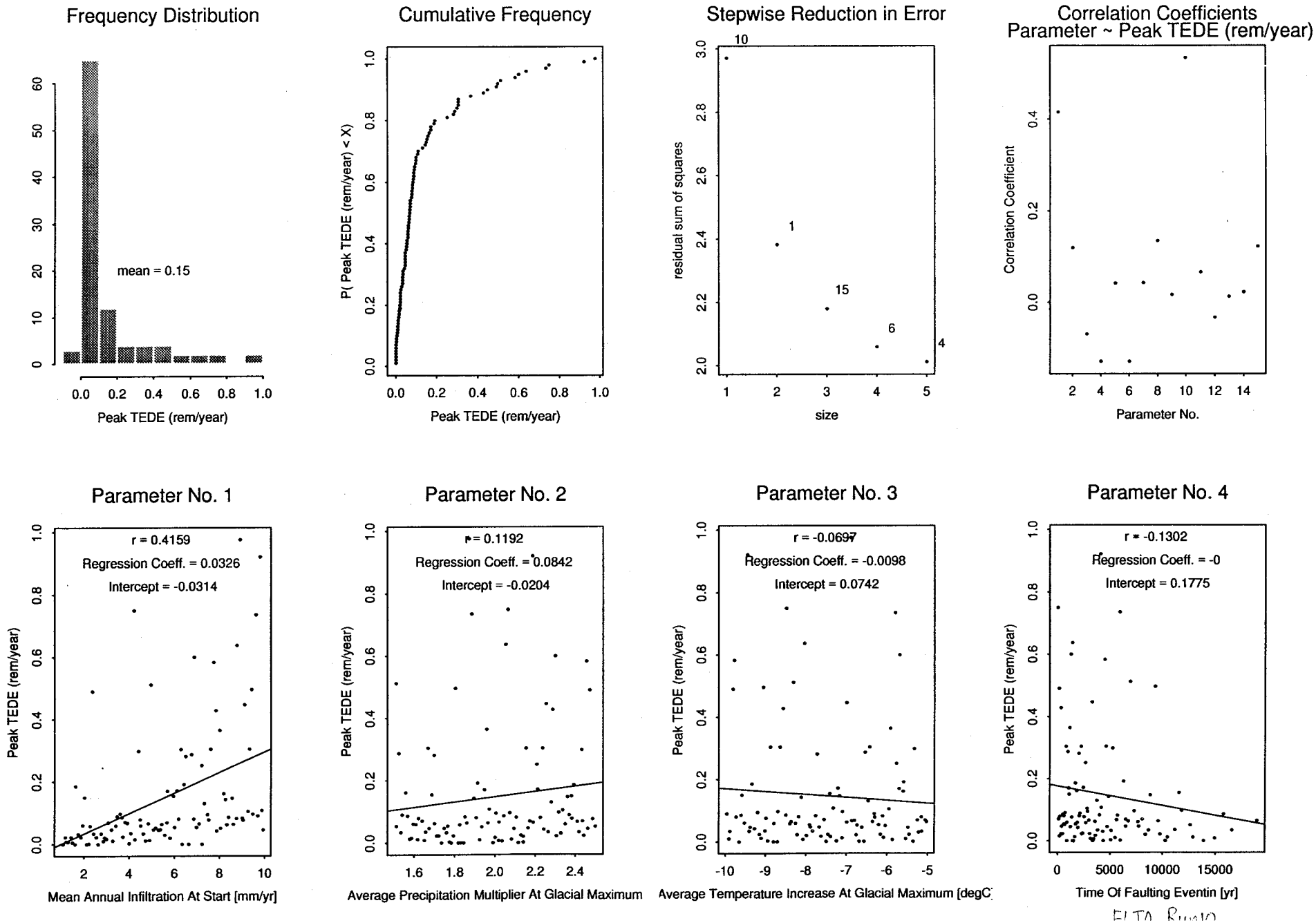
FLTO_Run10


Parameter No. 13
r = 0.0007
Regression Coeff. = 5534.3312
Intercept = 128.8318
Number of Waste Packages Disrupted
0
100
200
300
400
500
600
0.0
0.00001
0.00003
0.00005
Flow Factor

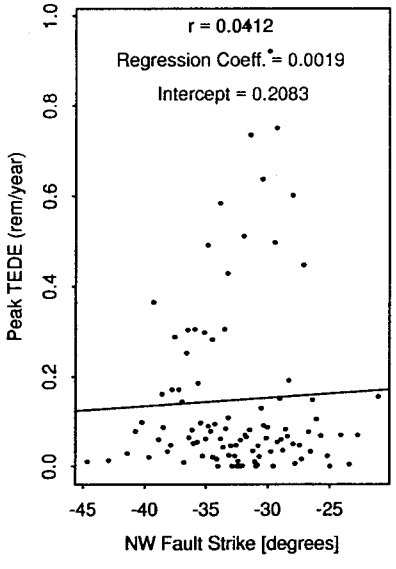

Parameter No. 14
r = 0.0077
Regression Coeff. = 60401.5732
Intercept = 127.4591
Number of Waste Packages Disrupted
0
100
200
300
400
500
600
0.0
0.00001
0.00003
0.00005
Fmult Factor


Parameter No. 15
r = -0.0251
Regression Coeff. = -10.4692
Intercept = 131.6899
Number of Waste Packages Disrupted
0
100
200
300
400
500
600
0.0
0.5
1.0
1.5
SubArea Wet Fraction

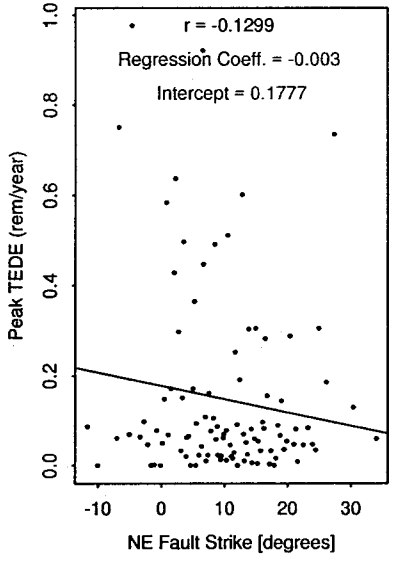
5 km Scenario
Summary Plots for Peak TEDE (rem/year)



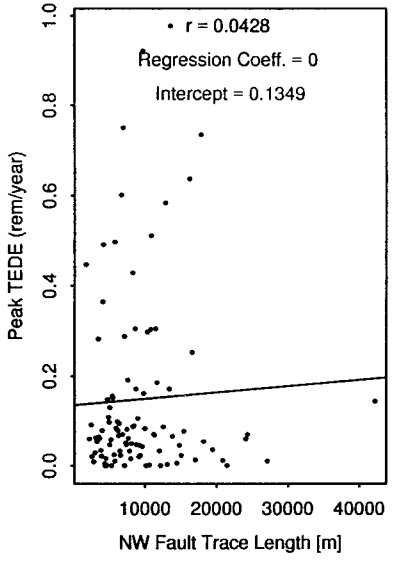
Parameter No. 5



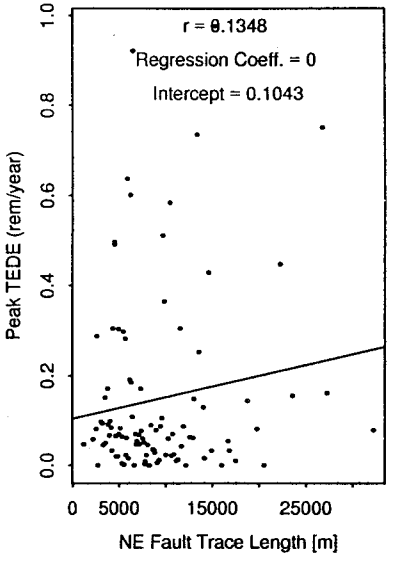
Parameter No. 6



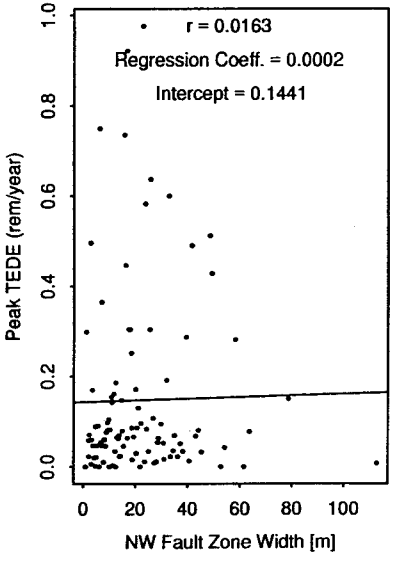
Parameter No. 7



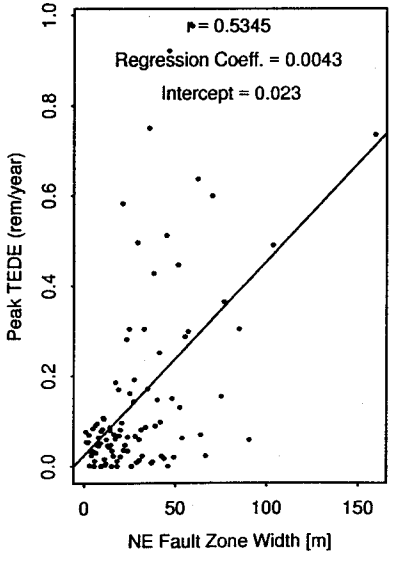
Parameter No. 8



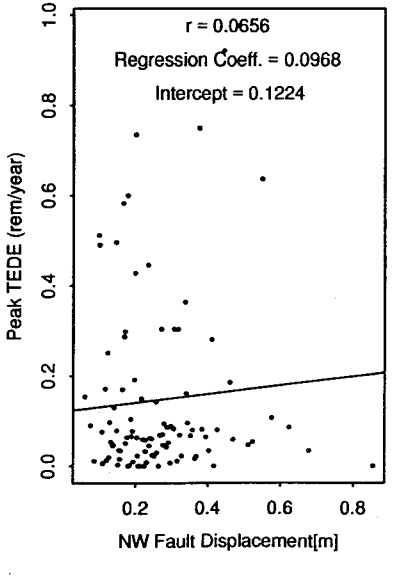
Parameter No. 9



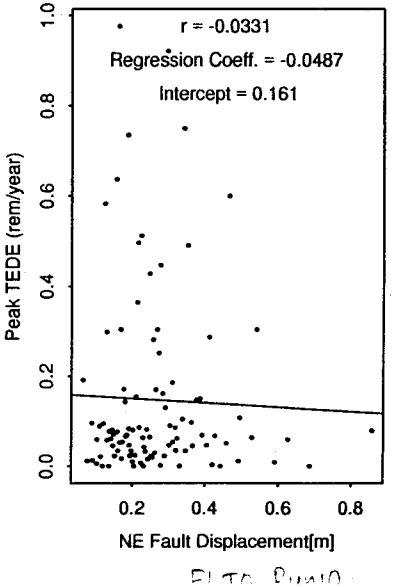
Parameter No. 10

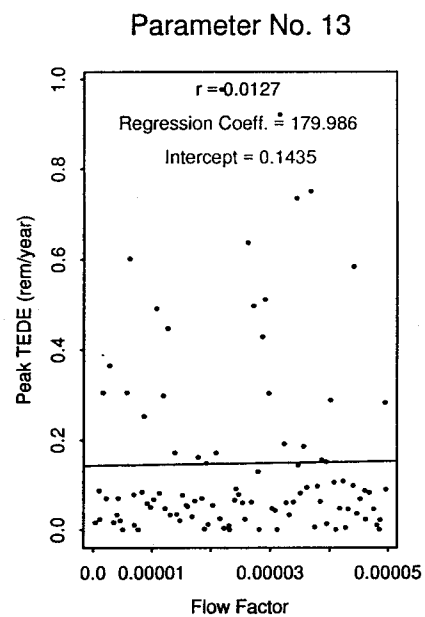


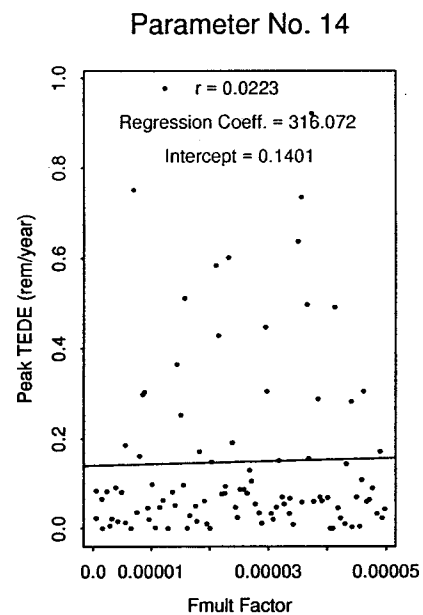
Parameter No. 11

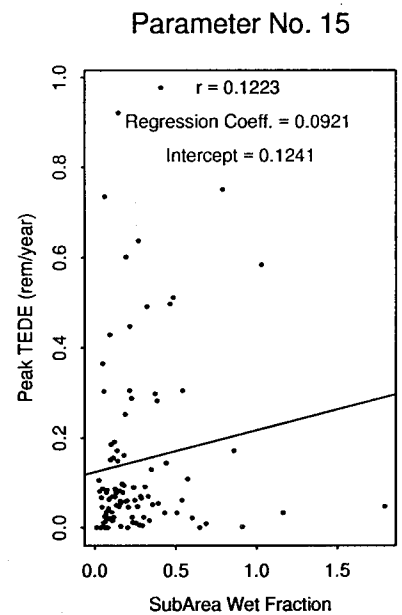


Parameter No. 12




Parameter No. 13
r = 0.0127
Regression Coeff. = 179.986
Intercept = 0.1435
Peak TEDE (rem/year)
0.0
0.2
0.4
0.6
0.8
1.0
0.0 0.00001 0.00003 0.00005
Flow Factor

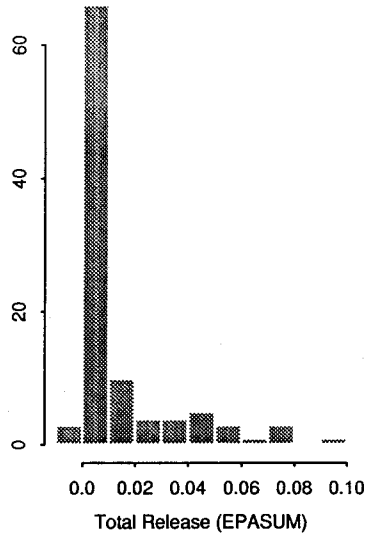

Parameter No. 14
r = 0.0223
Regression Coeff. = 316.072
Intercept = 0.1401
Peak TEDE (rem/year)
0.0
0.2
0.4
0.6
0.8
1.0
0.0 0.00001 0.00003 0.00005
Fmult Factor


Parameter No. 15
r = 0.1223
Regression Coeff. = 0.0921
Intercept = 0.1241
Peak TEDE (rem/year)
0.0
0.2
0.4
0.6
0.8
1.0
0.0 0.5 1.0 1.5
SubArea Wet Fraction

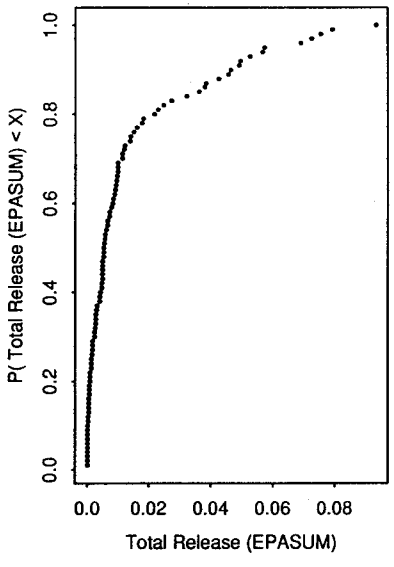
ELTA Run10

5 km Scenario
Summary Plots for Total Release (EPASUM)

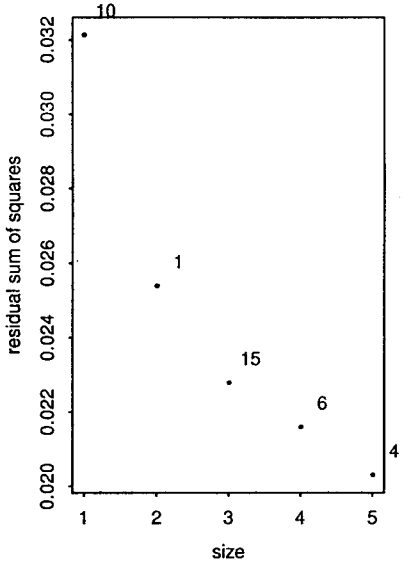
Frequency Distribution



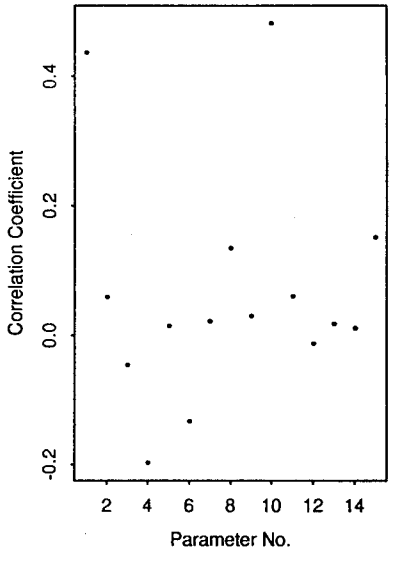
Cumulative Frequency



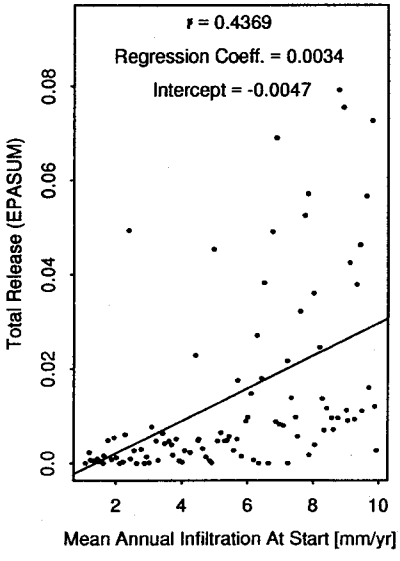
Stepwise Reduction in Error



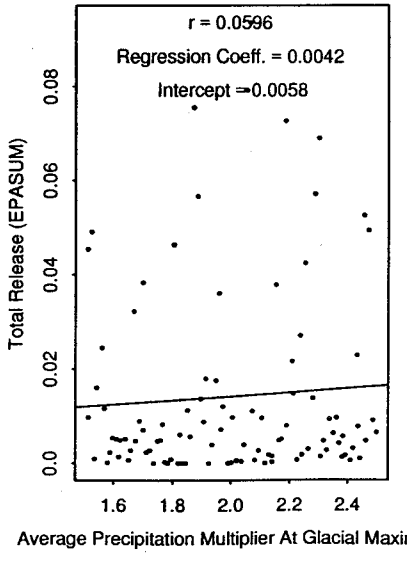
Correlation Coefficients
Parameter ~ Total Release (EPASUM)



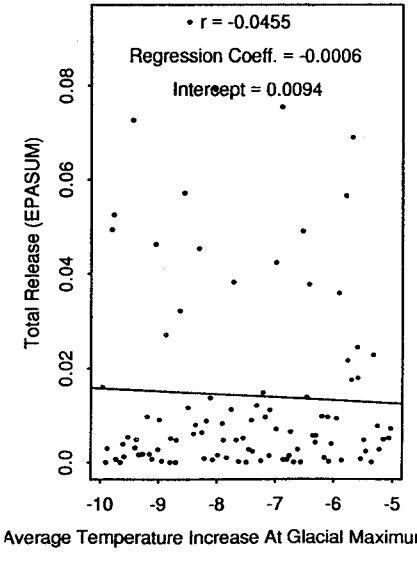
Parameter No. 1



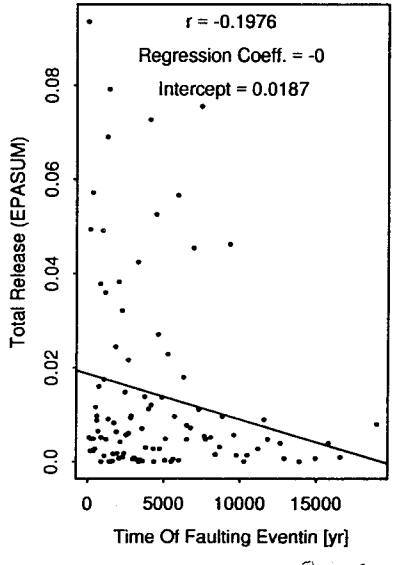
Parameter No. 2



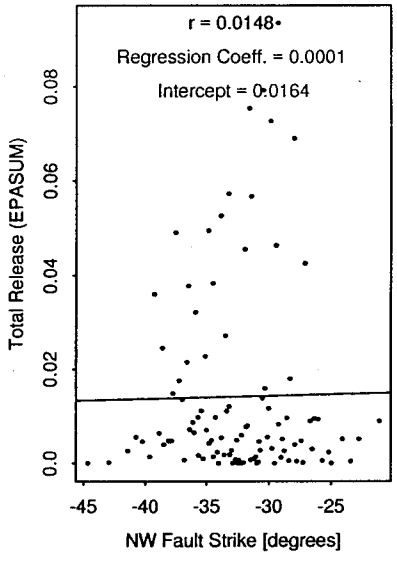
Parameter No. 3



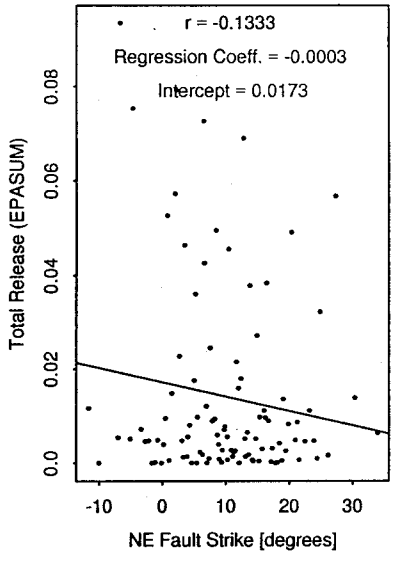
Parameter No. 4



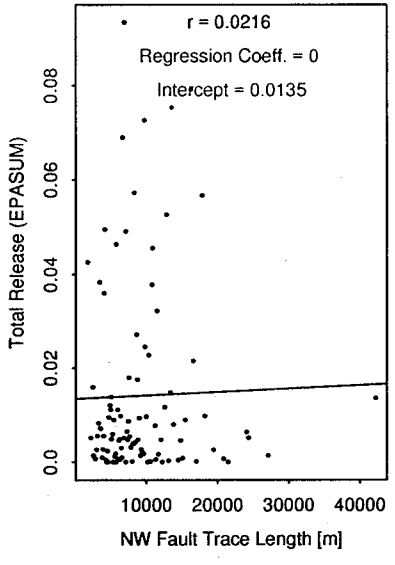
Parameter No. 5



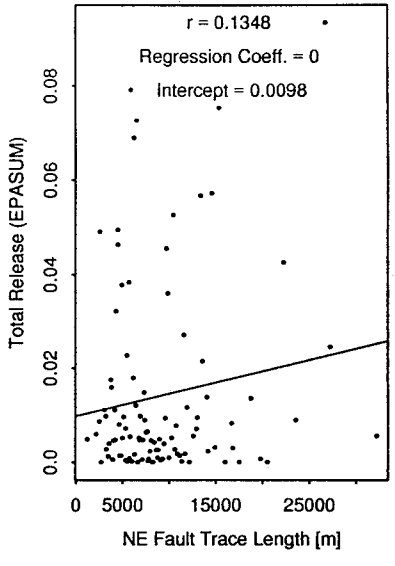
Parameter No. 6



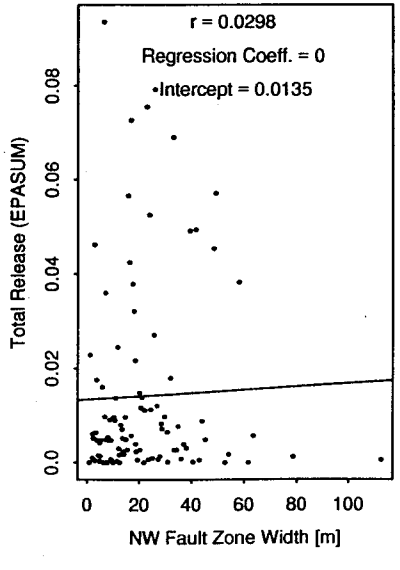
Parameter No. 7



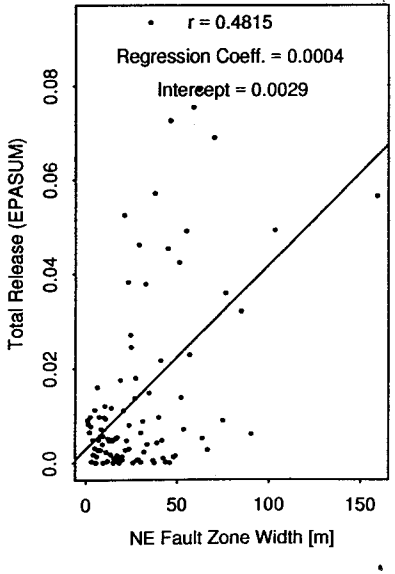
Parameter No. 8



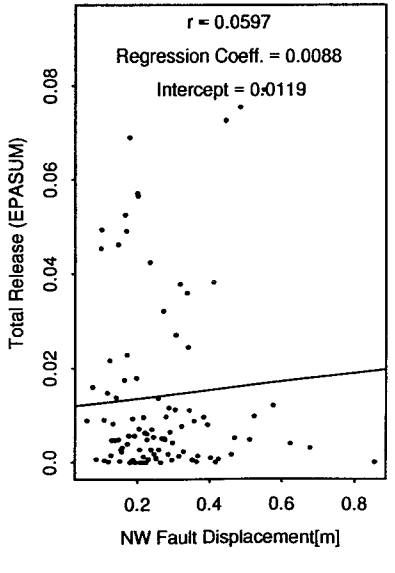
Parameter No. 9



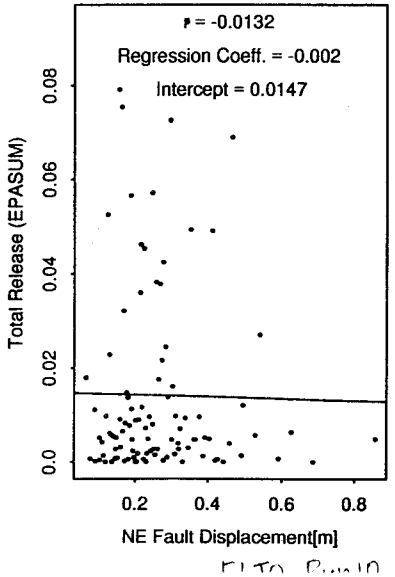
Parameter No. 10



Parameter No. 11

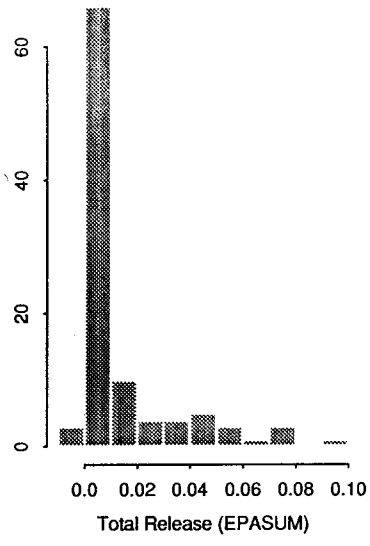


Parameter No. 12

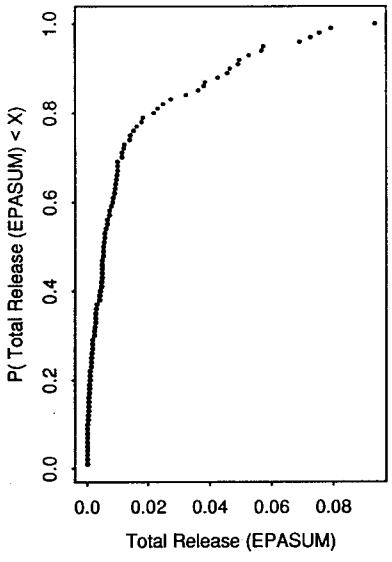


5 km Scenario
Summary Plots for Total Release (EPASUM)

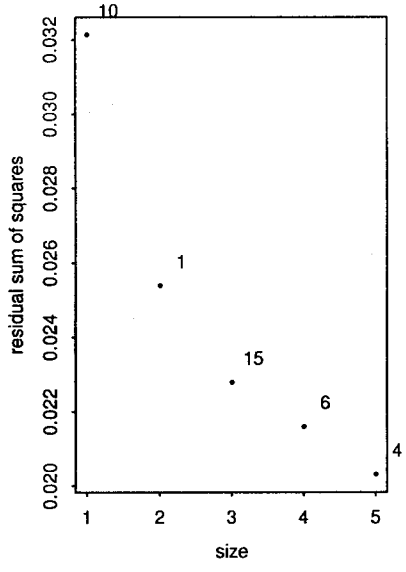
Frequency Distribution



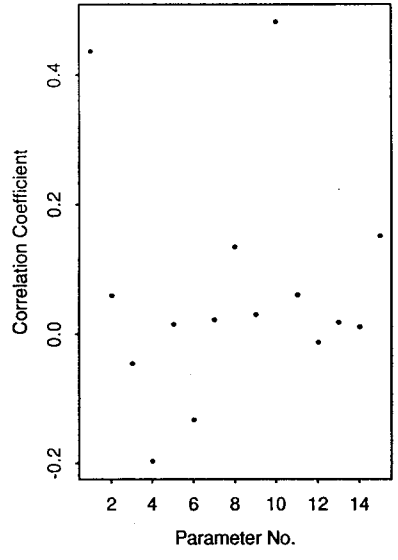
Cumulative Frequency



Stepwise Reduction in Error



Correlation Coefficients
Parameter ~ Total Release (EPASUM)



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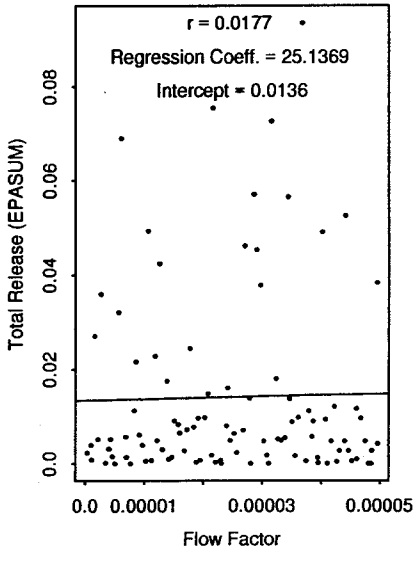

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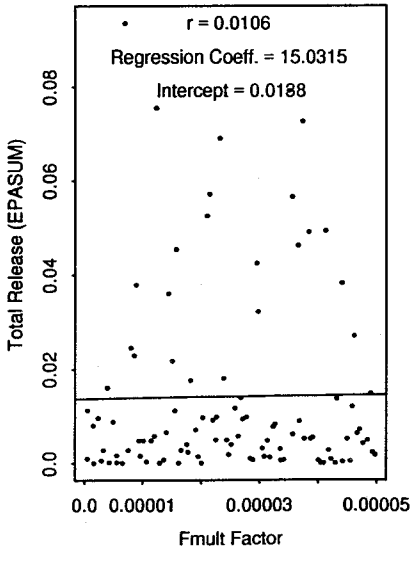
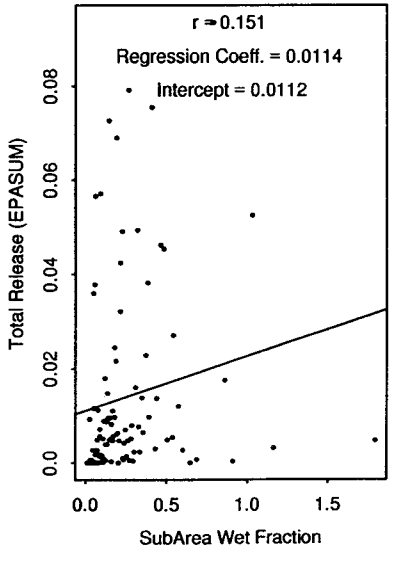


Parameter No. 15



FLTO - Run10

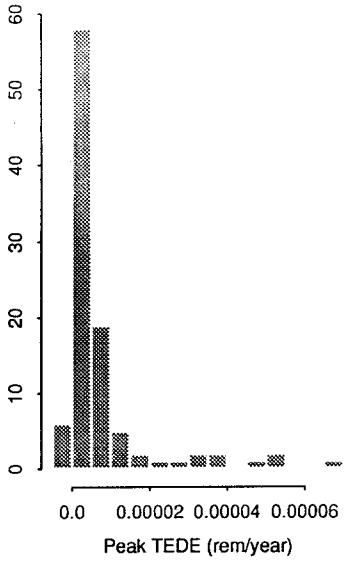
APPENDIX L:

Run: FLTO_Run11

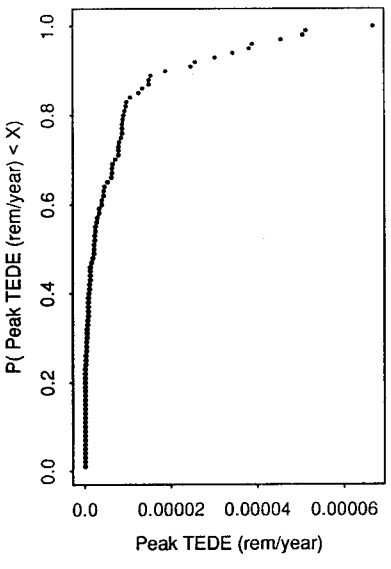
Distance to Focused Group = 20 km
Recurrence Interval = 5,000 years
Only FAULTO with Diffused Corrosion
Without Backfill

20 km Scenario
Summary Plots for Peak TEDE (rem/year)

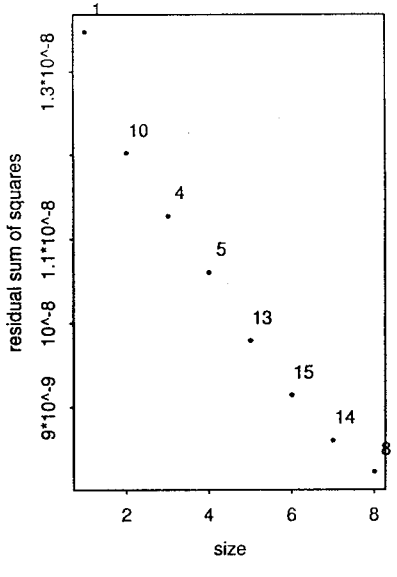
Frequency Distribution



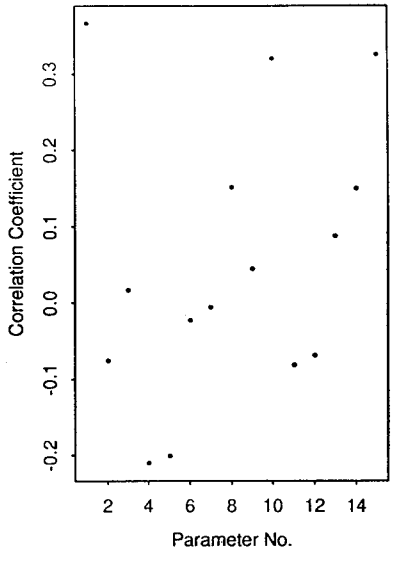
Cumulative Frequency



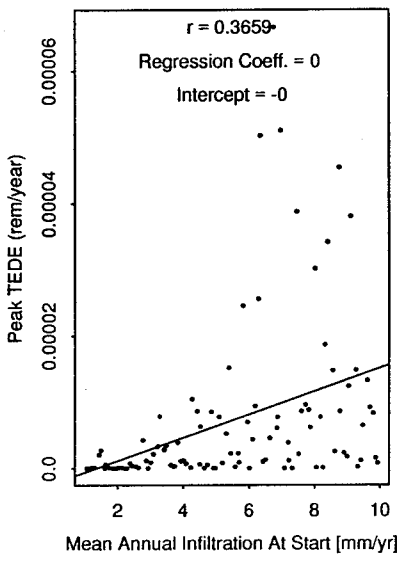
Stepwise Reduction in Error



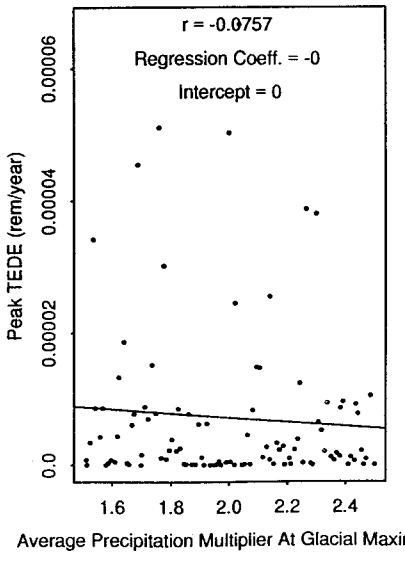
Correlation Coefficients
Parameter ~ Peak TEDE (rem/year)



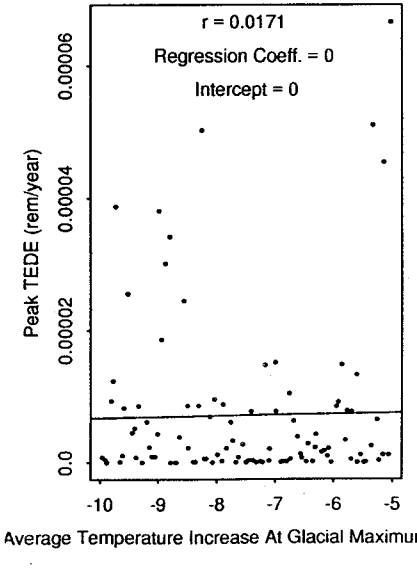
Parameter No. 1



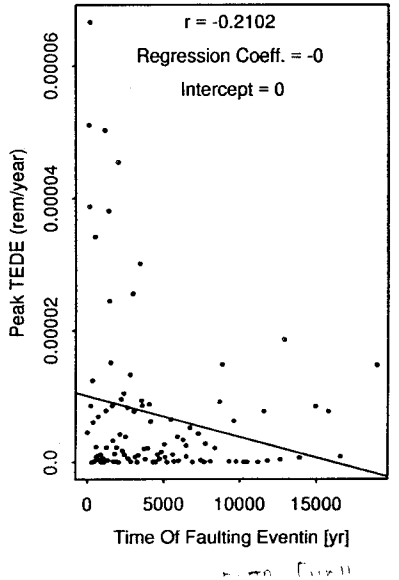
Parameter No. 2



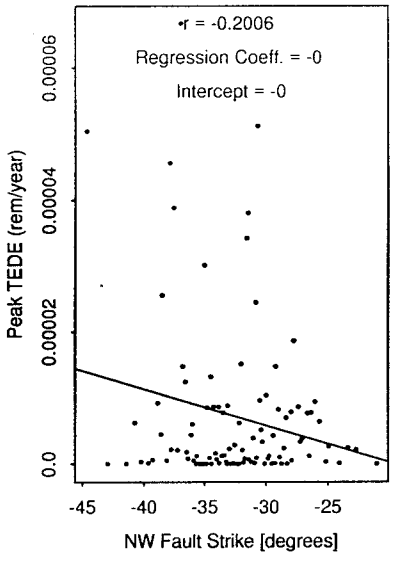
Parameter No. 3



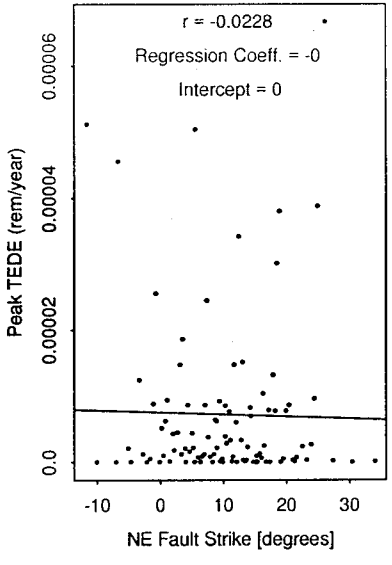
Parameter No. 4



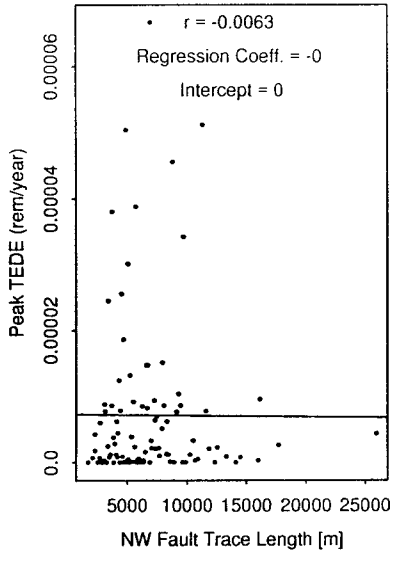
Parameter No. 5



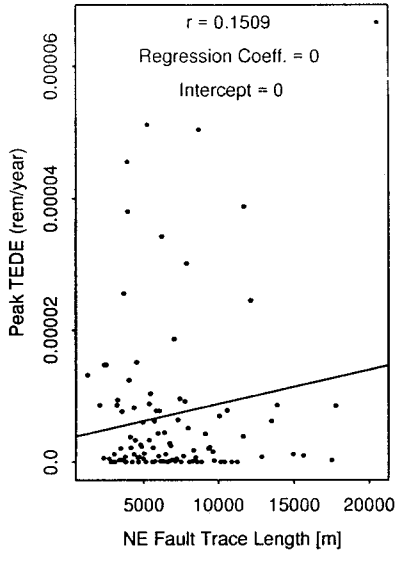
Parameter No. 6



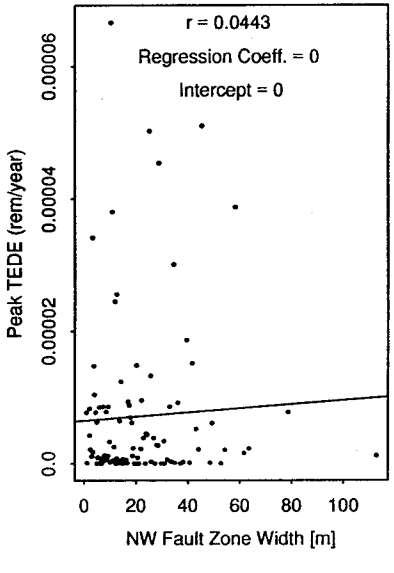
Parameter No. 7



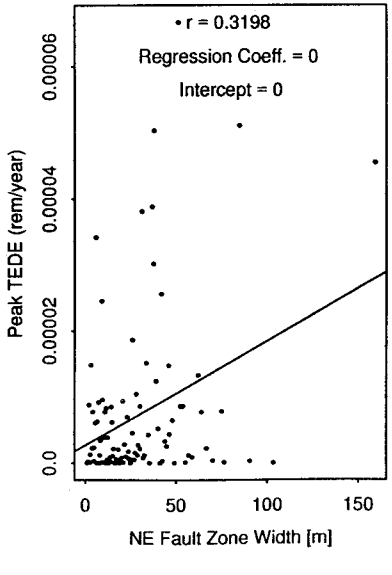
Parameter No. 8



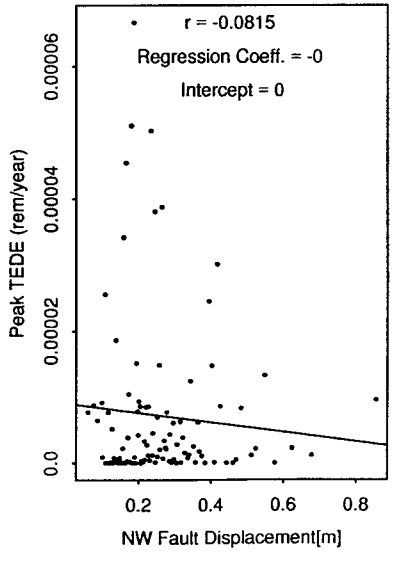
Parameter No. 9



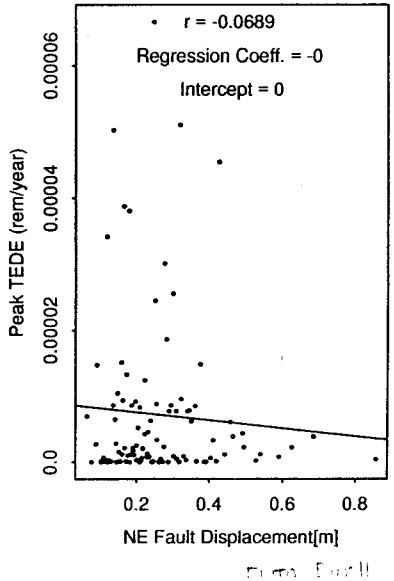
Parameter No. 10



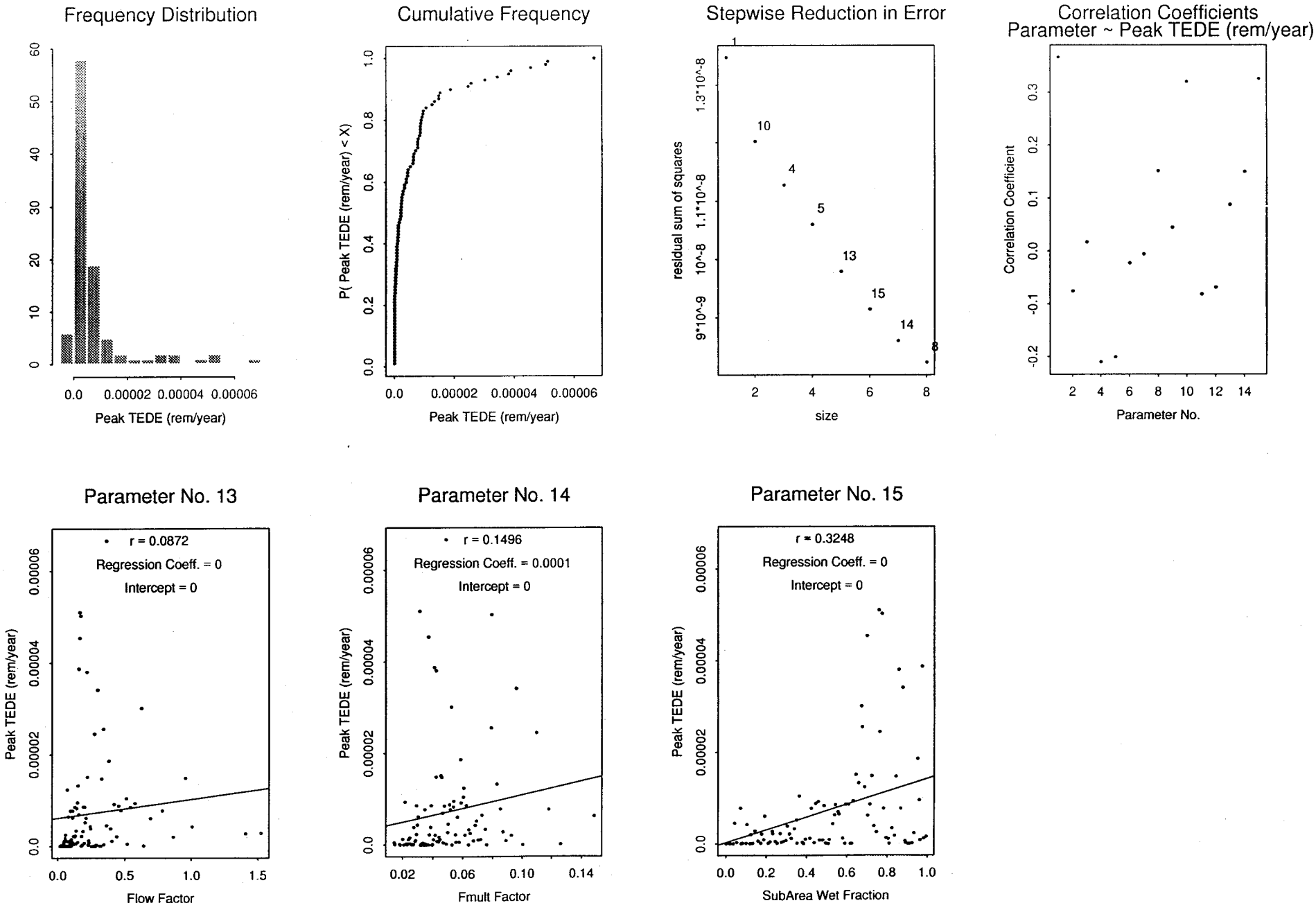
Parameter No. 11



Parameter No. 12

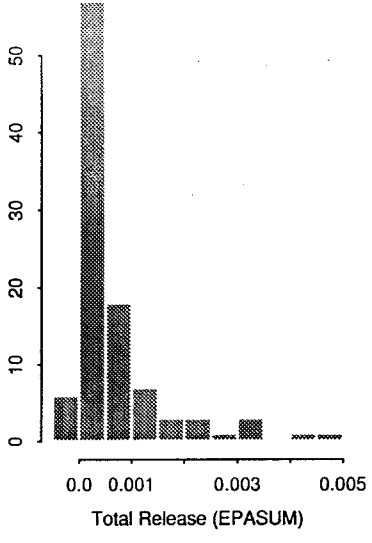


20 km Scenario
Summary Plots for Peak TEDE (rem/year)

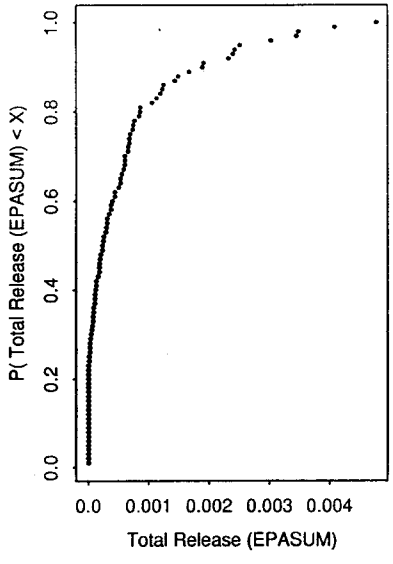


20 km Scenario
Summary Plots for Total Release (EPASUM)

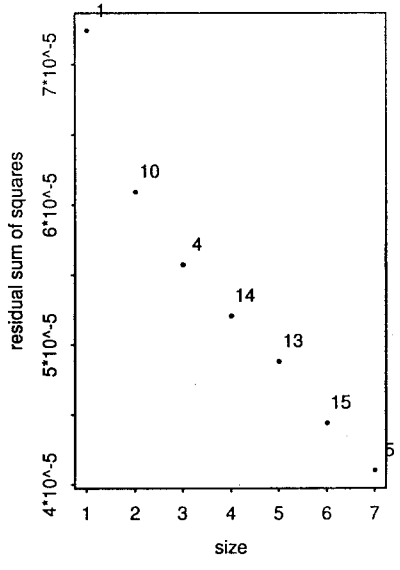
Frequency Distribution



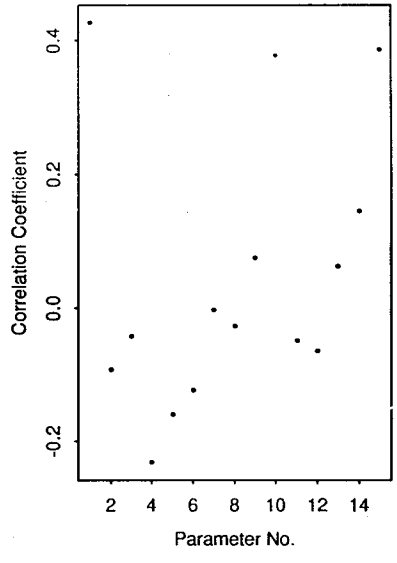
Cumulative Frequency



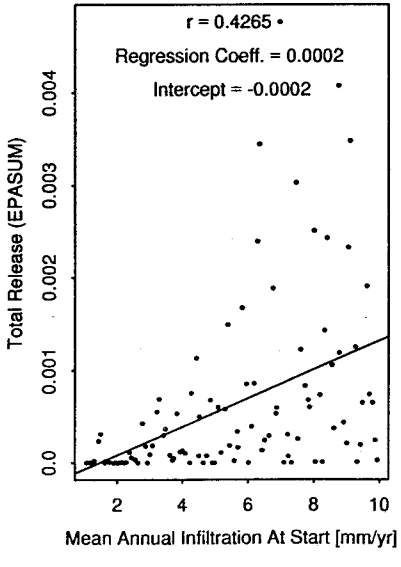
Stepwise Reduction in Error



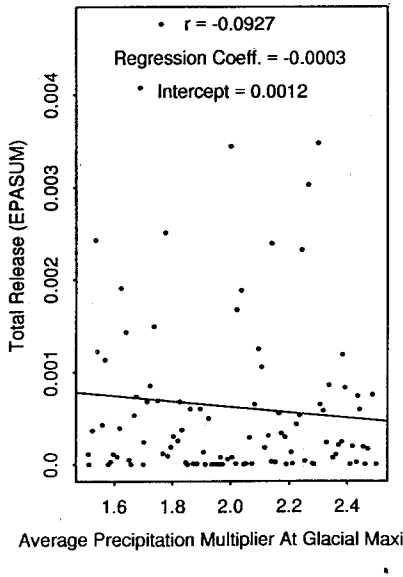
Correlation Coefficients
Parameter ~ Total Release (EPASUM)



Parameter No. 1



Parameter No. 2



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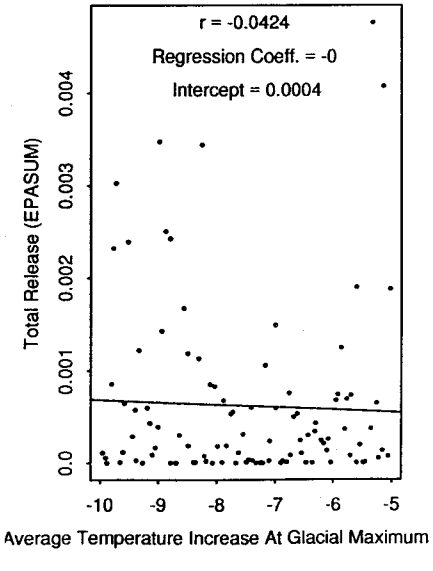
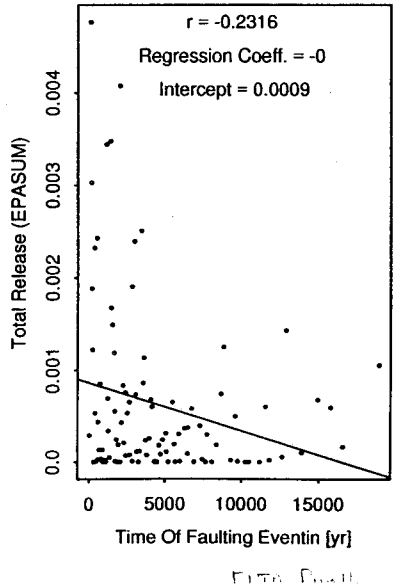


Parameter No. 4



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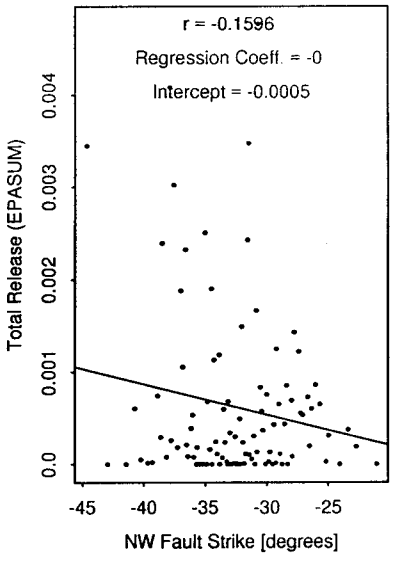

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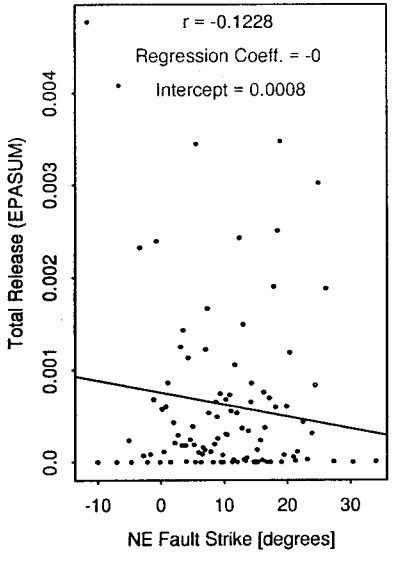

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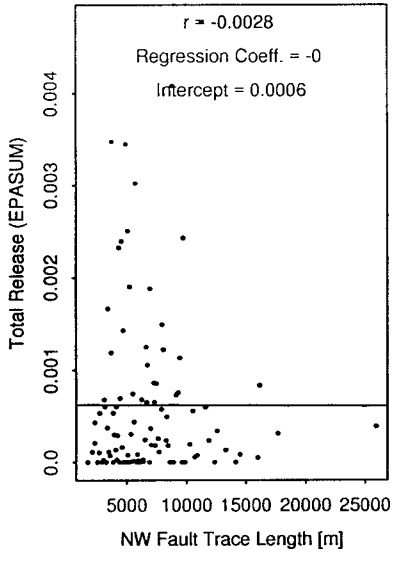
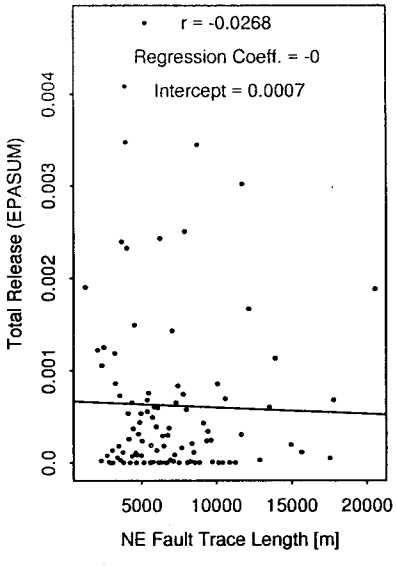


Parameter No. 8



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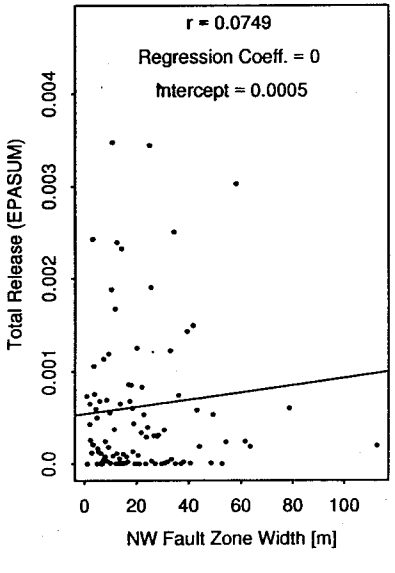

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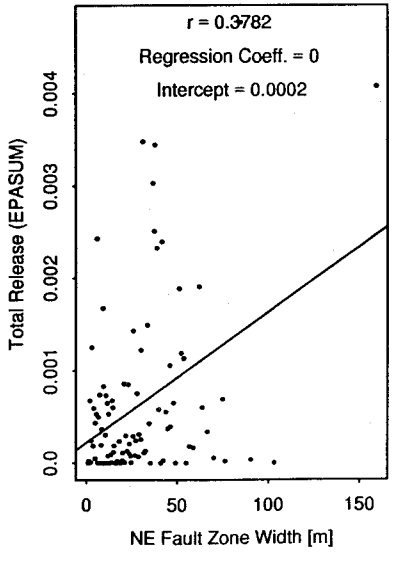
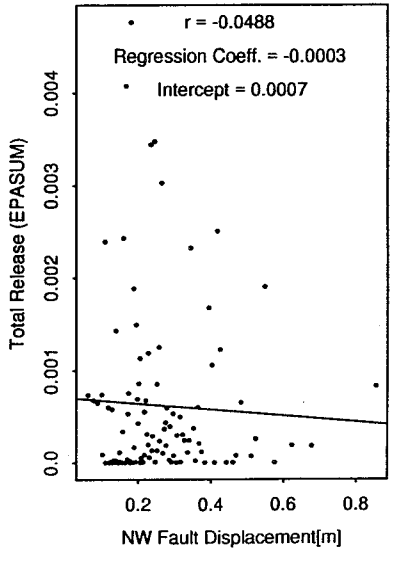
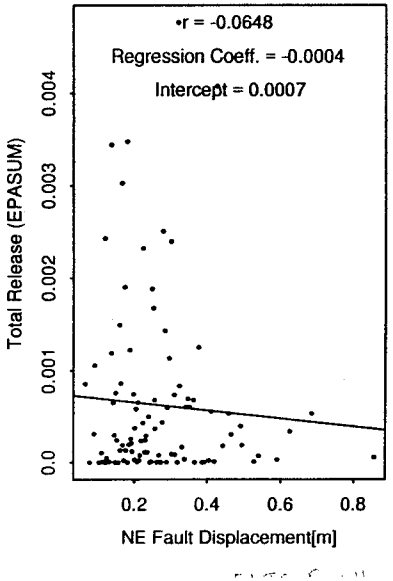


Parameter No. 11



Parameter No. 12



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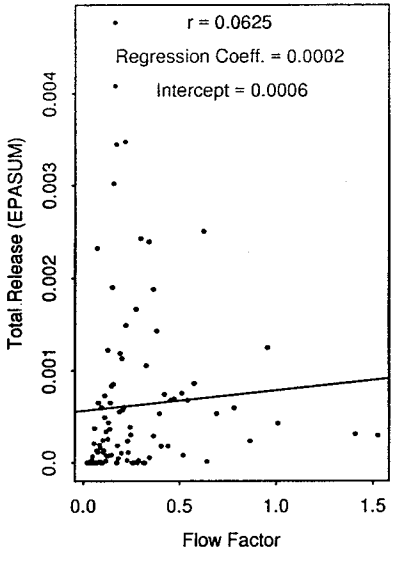
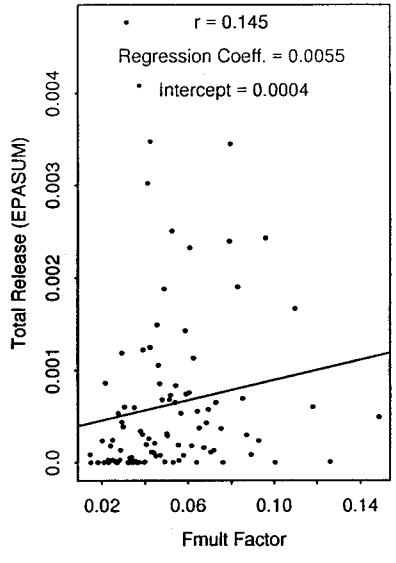
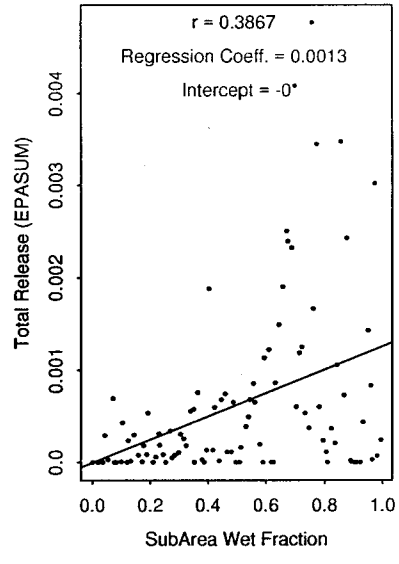


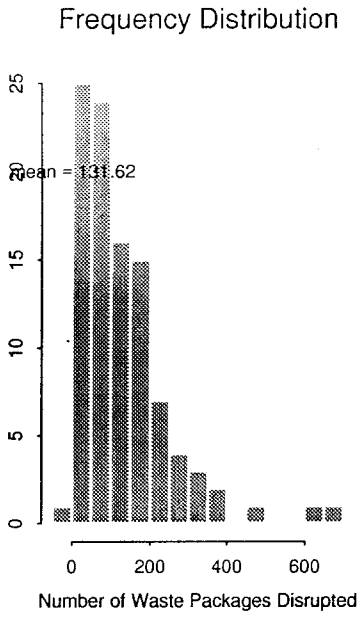
Parameter No. 14

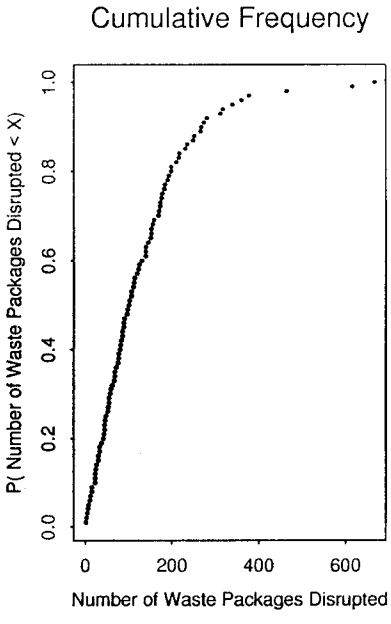


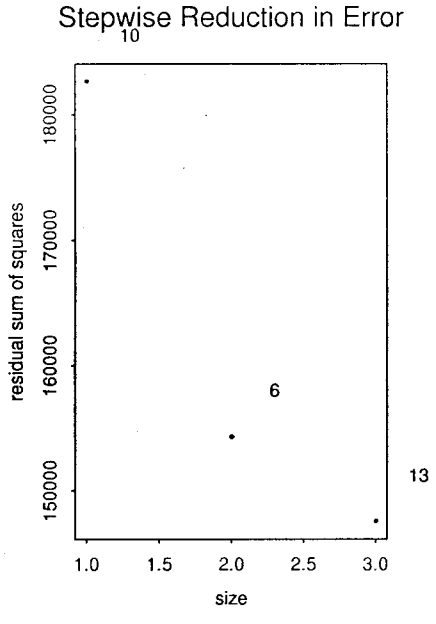
Parameter No. 15

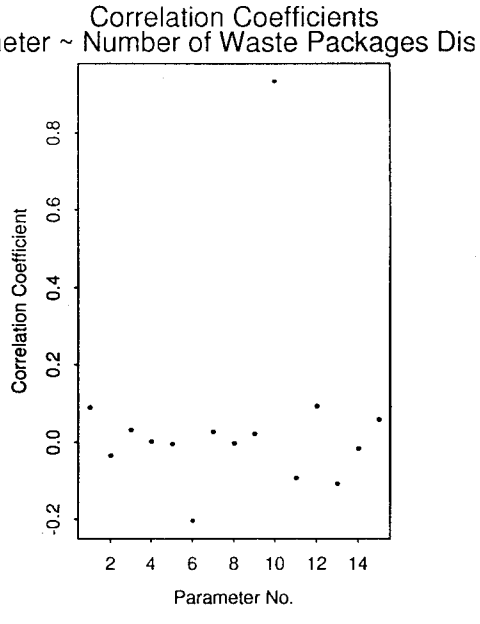


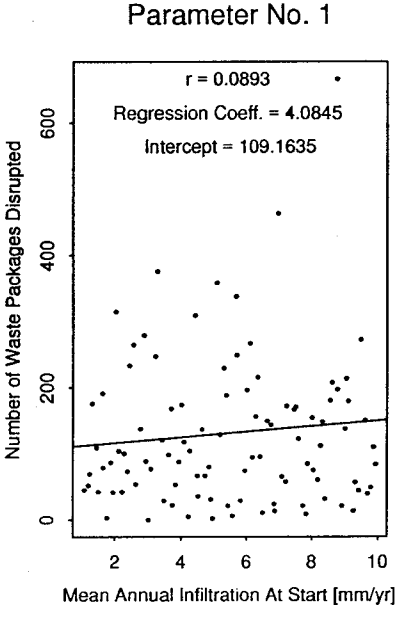
20 km Scenario
Summary Plots for Number of Waste Packages Disrupted

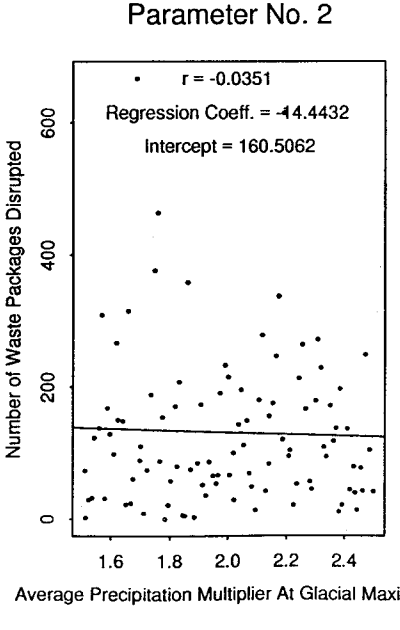


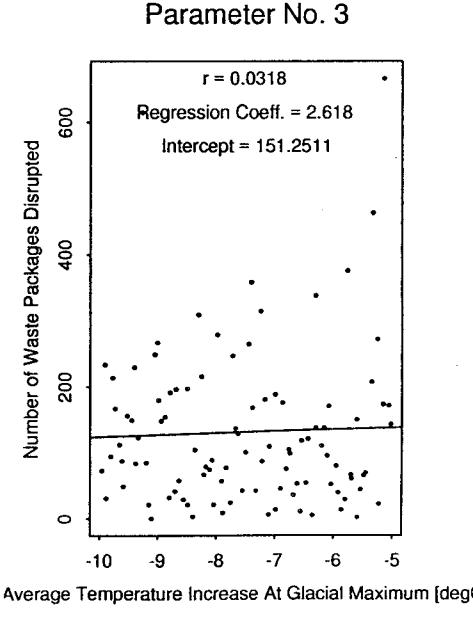


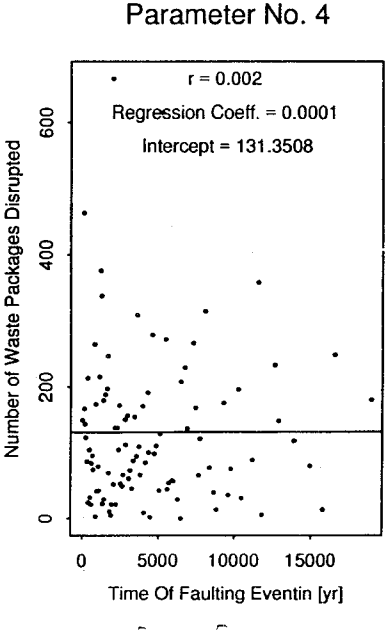




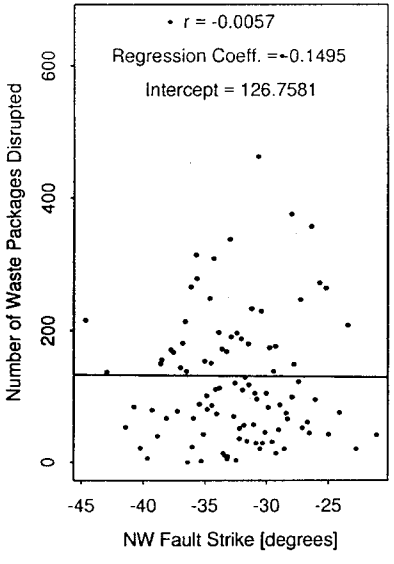




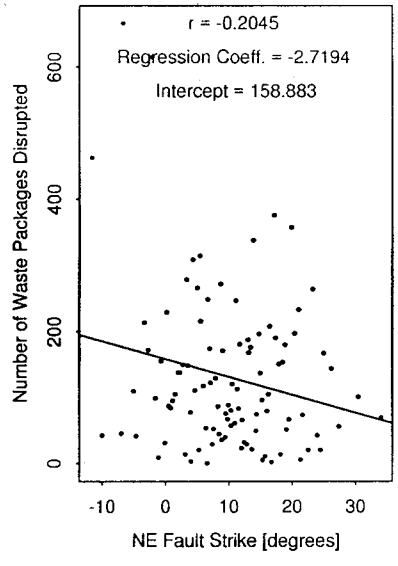




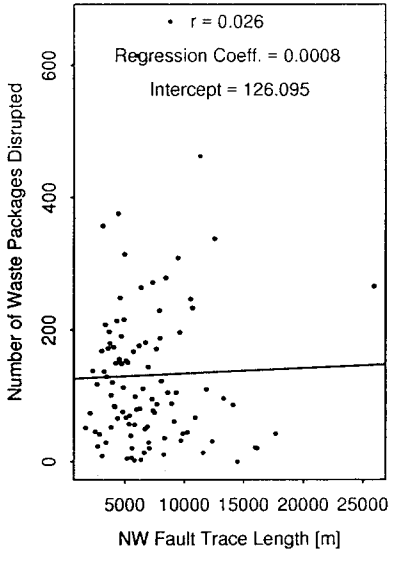
Parameter No. 5



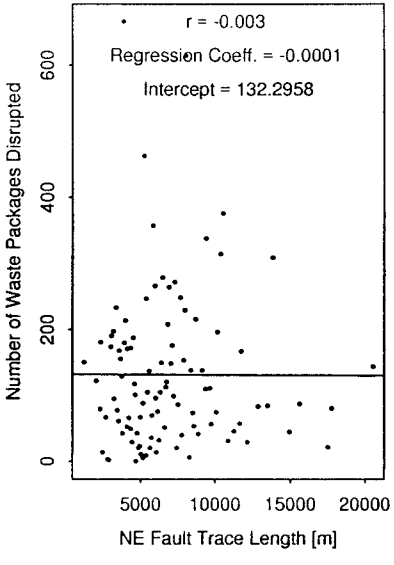
Parameter No. 6



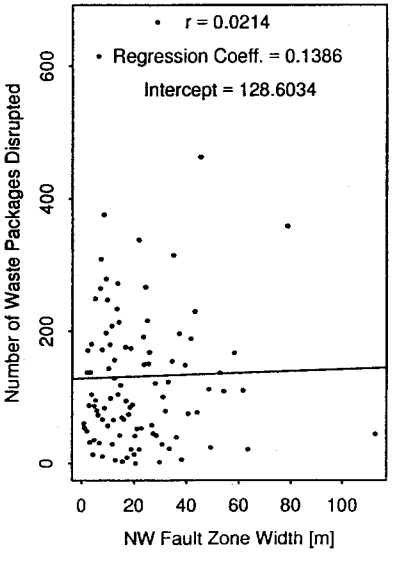
Parameter No. 7



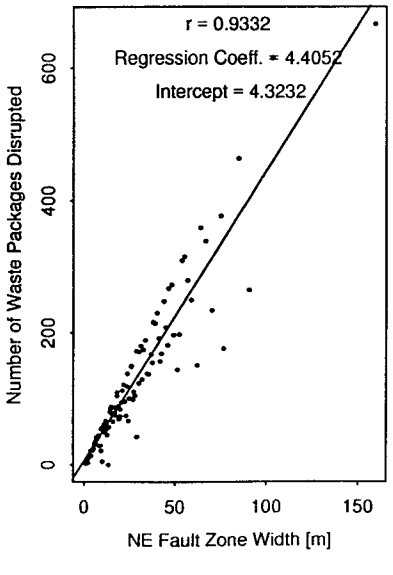
Parameter No. 8



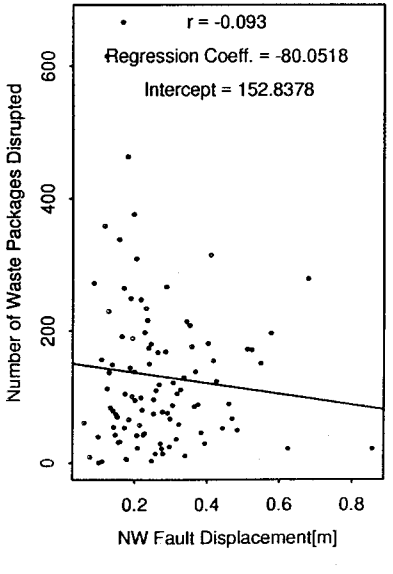
Parameter No. 9



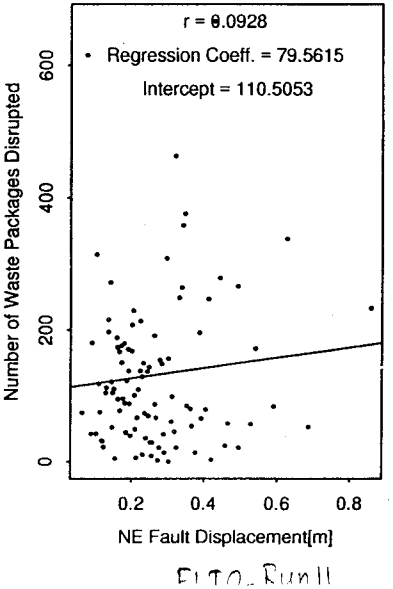
Parameter No. 10



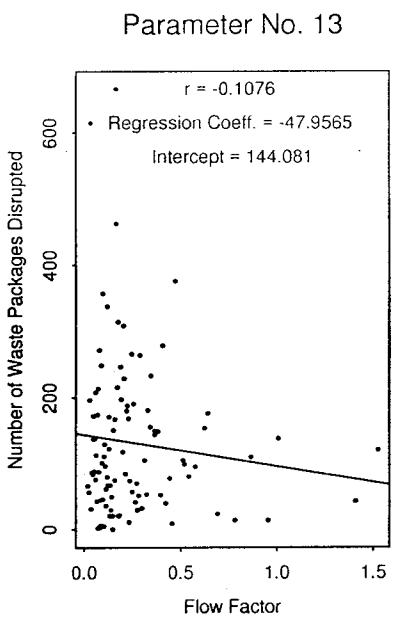
Parameter No. 11

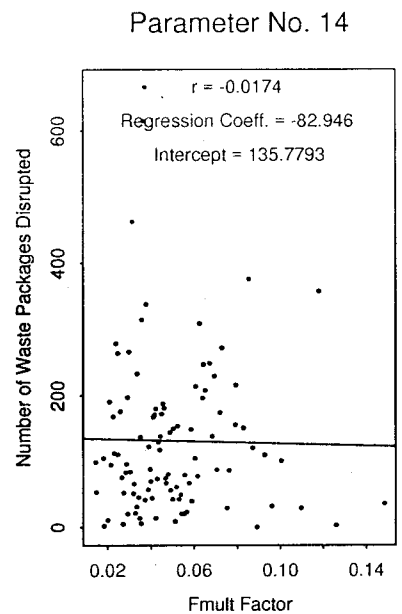


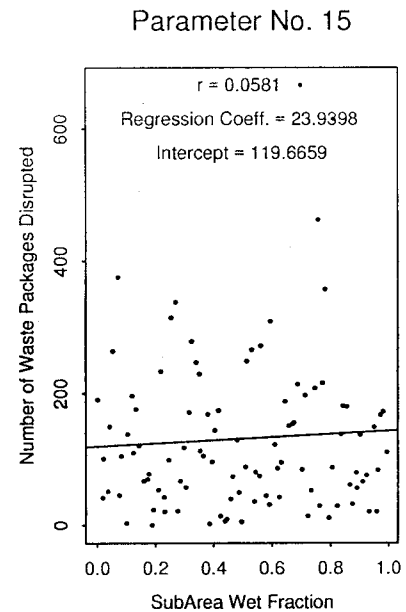
Parameter No. 12



FLTG_Run11


Parameter No. 13
r = -0.1076
Regression Coeff. = -47.9565
Intercept = 144.081
Number of Waste Packages Disrupted
0
200
400
600
0.0
0.5
1.0
1.5
Flow Factor


Parameter No. 14
r = -0.0174
Regression Coeff. = -82.946
Intercept = 135.7793
Number of Waste Packages Disrupted
0
200
400
600
0.02
0.06
0.10
0.14
Fmult Factor


Parameter No. 15
r = 0.0581
Regression Coeff. = 23.9398
Intercept = 119.6659
Number of Waste Packages Disrupted
0
200
400
600
0.0
0.2
0.4
0.6
0.8
1.0
SubArea Wet Fraction

FLTO. Run11

CENTER FOR NUCLEAR WASTE REGULATORY ANALYSES

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SCIENTIFIC NOTEBOOK
Development of the FAULTING Module

by

Amitava Ghosh

Southwest Research Institute
Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas

January 20, 1997

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1. INITIAL ENTRIES

Scientific NoteBook: # 167

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Project Title: Development of the FAULTING Module of Phase 3 IPA

Project Staff: Amitava Ghosh

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[Amitava Ghosh, February 28, 1996]

1.1. OBJECTIVES

The main task of the Structural Deformation and Seismicity (SDS) Key Technical Issue (KTI) is to analyze the probability and potential consequences of structural deformation and seismicity and related hazards to safe permanent storage of high-level nuclear waste at the candidate Yucca Mountain (YM), Nevada repository. As a part of that task, SDS KTI is evaluating the potential consequences of repository disruption from faulting. The potential consequence to faulting include rupture of waste packages (WP) directly from fault displacement. In essence, this evaluation tests Department of Energy (DOE) Waste Isolation and Containment Strategy (WICS) hypothesis regarding potential effects of structural deformation on waste package disruption. The hypothesis is:

- the amount of movement on faults through the repository horizon will be too small to bring waste to the surface, and too small and infrequent to significantly impact containment during the next few thousand years (H13).

The present study examines the sensitivity of performance of the proposed repository to input parameters in the FAULTO module of the total system performance assessment (TPA) code version 3.1.1. Sensitivity of input parameters to these modules is determined by their effect on the number of WPs affected and peak dose to assumed critical groups located 5 and 20 km from the proposed repository site. The FAULTO module was adapted from a stand-alone computer program called FAULTING (version 1.0) (Ghosh et al., 1997). The present analyses do not examine coupled processes, for example (i) simultaneous faulting, volcanism, and seismicity; (ii) enhanced WP degradation from seismicity or faulting; (iii) modifications of groundwater flow in the saturated and unsaturated zones from faulting or

seismicity; (iv) modifications to the near field environment from faulting and seismicity, or (v) degradation of WP strength with time due to corrosion followed by subsequent seismicity or faulting.

Sensitivity of different parameters of the FAULTO module was studied by running the TPA code. Correlation between the performance [described by three parameters – number of waste packages disrupted, peak TEDE, and total release (EPASUM)] and the input parameters were calculated using (i) linear regression and (ii) nonparametric or rank correlation. A computer program was written to calculate the rank correlation between two variables. The sections below describes the development of the program along with the verification runs.

[Amitava Ghosh, January 21, 1998]

1.2. COMPUTERS, COMPUTER CODES, AND DATA FILES

Table 1-1. Computer, operating system, and compiler used in the sensitivity analysis of FAULTO module

Machine Name	Machine Type	Operating System	Compiler	Location
bigbend	SUNSPACRstation 20	SUNOS 4.1	NONE	Building 189
snowwhite	SUN SPARCstation 20	SUNOS 4.1	f77 (SUN)	Building 189

[Amitava Ghosh, November 26, 1997]

1.3. MATHEMATICAL THEORY

Nonparametric or Rank Correlation has been used as the probability distribution function(s) from which both x_i and y_i were drawn was unknown. In Rank Correlation, each x_i is replaced by the value of the rank among all the other x_i's in thesample. The resulting list of numbers are drawn from a uniform distribution between 1 and N inclusive. If the x_i's are all distinct, then each integer will occur precisely once. If some of the x_i's have identical values, it is conventional to assign to all these ties the mean of the ranks that theywould have had if their values had been slightly different. Although there is some loss of information in relacing the original numbers by ranks, there is a major advantage of using Rank Correlation. If a correlation is demonstrated to be present nonparametrically, then there is real correlation. Nonparametric correlation is more robust than linear correlation and more resistant to unplanned defects in the data. Spearman Rank-Order Correlation Coefficient (Press et al., 1986) was used in this case.

Let R_i be the rank of x_i among other x's and S_i be the rank of y_i among other y's with ties being assigned the appropriate rank. Then the rank-order correlation coefficient is defined to be the linear correlation coefficient of the ranks:

$$r_s = \frac{\sum_i (R_i - R)(S_i - S)}{\sqrt{\sum_i (R_i - R)^2}\sqrt{\sum_i (S_i - S)^2}}$$

The significance of a nonzero value of r_s is tested by computing

$$t = r_s \sqrt{\frac{N-2}{1-r_s^2}}$$

which is distributed approximately as a Student's distribution with N-2 degrees of freedom.

r_s is closely related to another conventional measure of nonparameteric correlation, sum squared differenceof ranks

$$D = \sum_{i=1}^{N} (R_i - S_i)^2$$

When there are no ties in the data, then the exact relation between D and r_s is

$$r_s = 1 - \frac{6D}{N^3 - N}$$

When there are ties, the relationship is slightly complicated and is given by Press et al. (1986).

1.4. DEVELOPMENT OF CODE FOR RANK CORRELATION

A FORTRAN77 code to calculate the rank correlation between two variables have been developed using the subroutines given by Press et al. (1986). Only a front end is written to read the data from a file and to call the appropriate subroutines to carry out the calculations. The complete program is given below.

```
      PROGRAM rank_correlation

c
c*********************************************************************
c
c     This subroutine calculates Spearman Rank-Order Correlation
c     Coefficient. The main routine is designed to read the output
c     file from TPA 3.1.1 runs after combining results from
c     'relgwgs.res', 'samplpar.res', 'gwpkdos.res', and 'wpsfail.res'.
c
c     Subroutines adopted from:
c     Numerical Receipes: The Art of Scientific Computing
c     W.H. Press, B.P. Flannery, S.A. Teukolsky, and W.T. Vetterling
```

```
c       Cambridge University Press, Cambridge, 1986
c
c       Date of Last Modification: November 4, 1998
c       Author: Amitava Ghosh
c
c*************************************************************************
c


        IMPLICIT NONE

        INTEGER nmax
        PARAMETER (nmax=250)

        REAL data1(nmax),data2(nmax),wkspace1(nmax),wkspace2(nmax)
        REAL para(19,nmax)
        REAL d,zd,probd,rs,probrs

        INTEGER n,i,rd,columnx,columny

        CHARACTER datafile*80,response*1

        LOGICAL ondisk

        DATA rd /15/

c
c     Read data file name and open the file
c

12      WRITE (*,101) ' Data file => '
        READ  (*, '(a80)') datafile

        INQUIRE (FILE=datafile, EXIST=ondisk)

        IF (.NOT.ondisk) THEN
          WRITE (*,103) datafile
          GO TO 12
        END IF

        OPEN (rd,file=datafile,status='old')


c

200     WRITE (*,101)'Column Numbers for X and Y => '
        READ (*,*) columnx,columny

        REWIND (rd)

        n = 0

10      READ (rd,*,END=20) (para(i,n+1), i = 1, 19)

        data1(n+1) = para(columnx,n+1)
```

```
      data2(n+1) = para(columny,n+1)

      n = n + 1
      GO TO 10

20    WRITE (*,*)n,' data read from file'

c

      DO i = 1, n

        WRITE (*,*)data1(i),data2(i)

      END DO


c
c... Calculate Spearman Rand-Order Correlation
c

      CALL spear(data1,data2,n,wkspace1,wkspace2,d,zd,probd,rs,probrs)

      WRITE (*,110) d
      WRITE (*,111) zd
      WRITE (*,112) probd
      WRITE (*,113) rs
      WRITE (*,114) probrs
      WRITE (*,115)

c
c... Ask for another run
c

      WRITE (*,101)'Another Run (y/n) => '
      READ (*,'(a)') response

      IF (response.EQ.'y'.OR.response.EQ.'Y') THEN

        GOTO 200

      END IF

c
c... Format statements
c


101   FORMAT(//a40,$)
103   FORMAT(//'File does not exist. Please try again ...'//)

110   FORMAT (//'Sum-Squared Difference of Ranks D = ',f15.7)
111   FORMAT (//'Number of Standard Deviations by which D Deviates',/
     &          'from its Null Hypothesis Expected Value ZD = ',f15.7)
112   FORMAT (//'Two-Sided Significance Level of This Deviation ',
     &          'PROBD = ',f15.7)
```

```
113     FORMAT (///'Spearman Rank Correlation R_s = ',f15.7)
114     FORMAT (///'Two-Sided Significance Level of This Deviation ',/
     &            'from Zero PROBRS = ',f15.7)
115     FORMAT ((//'A small value of either PROBD or PROBRS indicates:',
     &           //'A SIGNIFICANT correlation (RS positive) or '
     &           //'A SIGNIFICANT anticorrelation (RS negative)'//)

        STOP
        END

c
c

        SUBROUTINE spear(data1,data2,n,wksp1,wksp2,d,zd,probd,rs,probrs)
        DIMENSION data1(n),data2(n),wksp1(n),wksp2(n)

c
c**********************************************************************
c       Given two data arrays, data1 and data2, each of length n, and
c       given two work spaces of equal length, this subroutine returns
c       their sum-squared difference of ranks as d, the number of
c       standard deviations by which D deviates from its null hypothesis
c       expected value as zd, the two sided significance level of this
c       deviation as probd, Spearman's rank correlation as rs, and the
c       two sided significance level of its deviation from zero as
c       probrs. A small value of either probd or probrs indicates a
c       significant correlation (rs positive) or anticorrelation (rs
c       negative).
c
c       Subroutines adopted from:
c       Numerical Receipes: The Art of Scientific Computing
c       W.H. Press, B.P. Flannery, S.A. Teukolsky, and W.T. Vetterling
c       Cambridge University Press, Cambridge, 1986
c**********************************************************************
c
```

Information potentially subject to copyright protection was redacted from this location. The redacted material is from

Press, W.H., B.P. Flannery, S.A. Teukolsky, and W. T. Vetterling.

The Art of Scientific Computing." Cambridge, Mass: Cambridge University Press. 1986.

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The Art of Scientific Computing." Cambridge, Mass: Cambridge University Press. 1986.

```
c**********************************************************************
c       Given a sorted array w of n elements, replaces the elements by
c       their rank, including midranking of ties, and returns as s the
c       sum of f^3 - f, where f is the number of elements in each tie.
c
c       Subroutines adopted from:
c       Numerical Receipes: The Art of Scientific Computing
c       W.H. Press, B.P. Flannery, S.A. Teukolsky, and W.T. Vetterling
c       Cambridge University Press, Cambridge, 1986
c**********************************************************************
c
```

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The Art of Scientific Computing." Cambridge, Mass: Cambridge University Press. 1986.

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The Art of Scientific Computing." Cambridge, Mass: Cambridge University Press. 1986.

```
c
c*********************************************************************
c      Sorts an array ra of length n into ascending numerical order
c      using the Heapsort algorithm, while making the corresponding
c      rearrangement of the array rb.
c
c      Subroutines adopted from:
c      Numerical Receipes: The Art of Scientific Computing
c      W.H. Press, B.P. Flannery, S.A. Teukolsky, and W.T. Vetterling
c      Cambridge University Press, Cambridge, 1986
c*********************************************************************
c
```

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```
c
c*********************************************************************
c       Returns the value LN[gamma(xx)] for xx>0. Full accuracy is
c       obtained for xx>1. For 0<xx<1, the reflection formula can be
c       used.
c
c       Subroutines adopted from:
c       Numerical Receipes: The Art of Scientific Computing
c       W.H. Press, B.P. Flannery, S.A. Teukolsky, and W.T. Vetterling
c       Cambridge University Press, Cambridge, 1986
c*********************************************************************
c
```

Information potentially subject to copyright protection was redacted from this location. The redacted material is from

Press, W.H., B.P. Flannery, S.A. Teukolsky, and W.T. Vetterling. "The Art of Scientific Computing." Cambridge, Mass: Cambridge University Press. 1986.

```
c
c*********************************************************************
c       Returns the complementary error function erfc(x) with fractional
c       error everywhere less than 1.2e-7
c
c       Subroutines adopted from:
c       Numerical Receipes: The Art of Scientific Computing
c       W.H. Press, B.P. Flannery, S.A. Teukolsky, and W.T. Vetterling
c       Cambridge University Press, Cambridge, 1986
```

```
c**********************************************************************
c
```

Information potentially subject to copyright protection was redacted from this location. The redacted material is from

Press, W.H., B.P. Flannery, S.A. Teukolsky, and W.T. Vetterling. "The Art of Scientific Computing." Cambridge, Mass: Cambridge University Press. 1986.

```
c
c
c
c**********************************************************************
c      Returns the incomplete beta function x(a,b)
c
c      Subroutines adopted from:
c      Numerical Receipes: The Art of Scientific Computing
c      W.H. Press, B.P. Flannery, S.A. Teukolsky, and W.T. Vetterling
c      Cambridge University Press, Cambridge, 1986
c**********************************************************************
c
```

Information potentially subject to copyright protection was redacted from this location. The redacted material is from

Press, W.H., B.P. Flannery, S.A. Teukolsky, and W.T. Vetterling. "The Art of Scientific Computing." Cambridge, Mass: Cambridge University Press. 1986.

```
c
```

Information potentially subject to copyright protection was redacted from this location. The redacted material is from

Press, W.H., B.P. Flannery, S.A. Teukolsky, and W.T. Vetterling. "The Art of Scientific Computing." Cambridge, Mass: Cambridge University Press. 1986.

```
c
c*******************************************************************
c       Continued fraction for incomplete beta function, used by betai
c
c       Subroutines adopted from:
c       Numerical Receipes: The Art of Scientific Computing
c       W.H. Press, B.P. Flannery, S.A. Teukolsky, and W.T. Vetterling
c       Cambridge University Press, Cambridge, 1986
c*******************************************************************
c
```

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1.5. VERIFICATION OF THE PROGRAM

The program was verified using four data sets. The data sets are given below.

Data Set: spear1.dat

```
1.0000 2.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000
1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000
2.0000 4.0000 2.0000 2.0000 2.0000 2.0000 2.0000 2.0000 2.0000 2.0000
2.0000 2.0000 2.0000 2.0000 2.0000 2.0000 2.0000 2.0000
3.0000 6.0000 3.0000 3.0000 3.0000 3.0000 3.0000 3.0000 3.0000 3.0000
3.0000 3.0000 3.0000 3.0000 3.0000 3.0000 3.0000 3.0000
4.0000 8.0000 4.0000 4.0000 4.0000 4.0000 4.0000 4.0000 4.0000 4.0000
4.0000 4.0000 4.0000 4.0000 4.0000 4.0000 4.0000 4.0000
5.0000 10.0000 5.0000 5.0000 5.0000 5.0000 5.0000 5.0000 5.0000 5.0000
5.0000 5.0000 5.0000 5.0000 5.0000 5.0000 5.0000 5.0000
6.0000 12.0000 6.0000 6.0000 6.0000 6.0000 6.0000 6.0000 6.0000 6.0000
6.0000 6.0000 6.0000 6.0000 6.0000 6.0000 6.0000 6.0000
7.0000 14.0000 7.0000 7.0000 7.0000 7.0000 7.0000 7.0000 7.0000 7.0000
7.0000 7.0000 7.0000 7.0000 7.0000 7.0000 7.0000 7.0000
8.0000 16.0000 8.0000 8.0000 8.0000 8.0000 8.0000 8.0000 8.0000 8.0000
8.0000 8.0000 8.0000 8.0000 8.0000 8.0000 8.0000 8.0000
9.0000 18.0000 9.0000 9.0000 9.0000 9.0000 9.0000 9.0000 9.0000 9.0000
9.0000 9.0000 9.0000 9.0000 9.0000 9.0000 9.0000 9.0000
10.0000 20.0000 10.0000 10.0000 10.0000 10.0000 10.0000 10.0000
10.0000 10.0000 10.0000 10.0000 10.0000 10.0000 10.0000 10.0000
10.0000 10.0000 10.0000
11.0000 22.0000 11.0000 11.0000 11.0000 11.0000 11.0000 11.0000
11.0000 11.0000 11.0000 11.0000 11.0000 11.0000 11.0000 11.0000
11.0000 11.0000 11.0000
```

```
12.0000 24.0000 12.0000 12.0000 12.0000 12.0000 12.0000 12.0000
12.0000 12.0000 12.0000 12.0000 12.0000 12.0000 12.0000 12.0000
12.0000 12.0000 12.0000
13.0000 26.0000 13.0000 13.0000 13.0000 13.0000 13.0000 13.0000
13.0000 13.0000 13.0000 13.0000 13.0000 13.0000 13.0000 13.0000
13.0000 13.0000 13.0000
14.0000 28.0000 14.0000 14.0000 14.0000 14.0000 14.0000 14.0000
14.0000 14.0000 14.0000 14.0000 14.0000 14.0000 14.0000 14.0000
14.0000 14.0000 14.0000
15.0000 30.0000 15.0000 15.0000 15.0000 15.0000 15.0000 15.0000
15.0000 15.0000 15.0000 15.0000 15.0000 15.0000 15.0000 15.0000
15.0000 15.0000 15.0000
16.0000 32.0000 16.0000 16.0000 16.0000 16.0000 16.0000 16.0000
16.0000 16.0000 16.0000 16.0000 16.0000 16.0000 16.0000 16.0000
16.0000 16.0000 16.0000
17.0000 34.0000 17.0000 17.0000 17.0000 17.0000 17.0000 17.0000
17.0000 17.0000 17.0000 17.0000 17.0000 17.0000 17.0000 17.0000
17.0000 17.0000 17.0000
18.0000 36.0000 18.0000 18.0000 18.0000 18.0000 18.0000 18.0000
18.0000 18.0000 18.0000 18.0000 18.0000 18.0000 18.0000 18.0000
18.0000 18.0000 18.0000
19.0000 38.0000 19.0000 19.0000 19.0000 19.0000 19.0000 19.0000
19.0000 19.0000 19.0000 19.0000 19.0000 19.0000 19.0000 19.0000
19.0000 19.0000 19.0000
20.0000 40.0000 20.0000 20.0000 20.0000 20.0000 20.0000 20.0000
20.0000 20.0000 20.0000 20.0000 20.0000 20.0000 20.0000 20.0000
20.0000 20.0000 20.0000
```

Only columns 1 and 2 are used for verification. Values in Column 2 are two times the value in Column 1.

Data Set: spear2.dat

```
1.0000 3.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000
1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000
2.0000 5.0000 2.0000 2.0000 2.0000 2.0000 2.0000 2.0000 2.0000 2.0000
2.0000 2.0000 2.0000 2.0000 2.0000 2.0000 2.0000 2.0000 2.0000
3.0000 7.0000 3.0000 3.0000 3.0000 3.0000 3.0000 3.0000 3.0000 3.0000
3.0000 3.0000 3.0000 3.0000 3.0000 3.0000 3.0000 3.0000 3.0000
4.0000 9.0000 4.0000 4.0000 4.0000 4.0000 4.0000 4.0000 4.0000 4.0000
4.0000 4.0000 4.0000 4.0000 4.0000 4.0000 4.0000 4.0000 4.0000
5.0000 11.0000 5.0000 5.0000 5.0000 5.0000 5.0000 5.0000 5.0000 5.0000
5.0000 5.0000 5.0000 5.0000 5.0000 5.0000 5.0000 5.0000 5.0000
6.0000 13.0000 6.0000 6.0000 6.0000 6.0000 6.0000 6.0000 6.0000 6.0000
6.0000 6.0000 6.0000 6.0000 6.0000 6.0000 6.0000 6.0000 6.0000
7.0000 15.0000 7.0000 7.0000 7.0000 7.0000 7.0000 7.0000 7.0000 7.0000
7.0000 7.0000 7.0000 7.0000 7.0000 7.0000 7.0000 7.0000 7.0000
```

```
8.0000 17.0000 8.0000 8.0000 8.0000 8.0000 8.0000 8.0000 8.0000 8.0000
8.0000 8.0000 8.0000 8.0000 8.0000 8.0000 8.0000 8.0000 8.0000
9.0000 19.0000 9.0000 9.0000 9.0000 9.0000 9.0000 9.0000 9.0000 9.0000
9.0000 9.0000 9.0000 9.0000 9.0000 9.0000 9.0000 9.0000 9.0000
10.0000 21.0000 10.0000 10.0000 10.0000 10.0000 10.0000 10.0000
10.0000 10.0000 10.0000 10.0000 10.0000 10.0000 10.0000 10.0000
10.0000 10.0000 10.0000
11.0000 23.0000 11.0000 11.0000 11.0000 11.0000 11.0000 11.0000
11.0000 11.0000 11.0000 11.0000 11.0000 11.0000 11.0000 11.0000
11.0000 11.0000 11.0000
12.0000 25.0000 12.0000 12.0000 12.0000 12.0000 12.0000 12.0000
12.0000 12.0000 12.0000 12.0000 12.0000 12.0000 12.0000 12.0000
12.0000 12.0000 12.0000
13.0000 27.0000 13.0000 13.0000 13.0000 13.0000 13.0000 13.0000
13.0000 13.0000 13.0000 13.0000 13.0000 13.0000 13.0000 13.0000
13.0000 13.0000 13.0000
14.0000 29.0000 14.0000 14.0000 14.0000 14.0000 14.0000 14.0000
14.0000 14.0000 14.0000 14.0000 14.0000 14.0000 14.0000 14.0000
14.0000 14.0000 14.0000
15.0000 31.0000 15.0000 15.0000 15.0000 15.0000 15.0000 15.0000
15.0000 15.0000 15.0000 15.0000 15.0000 15.0000 15.0000 15.0000
15.0000 15.0000 15.0000
16.0000 33.0000 16.0000 16.0000 16.0000 16.0000 16.0000 16.0000
16.0000 16.0000 16.0000 16.0000 16.0000 16.0000 16.0000 16.0000
16.0000 16.0000 16.0000
17.0000 35.0000 17.0000 17.0000 17.0000 17.0000 17.0000 17.0000
17.0000 17.0000 17.0000 17.0000 17.0000 17.0000 17.0000 17.0000
17.0000 17.0000 17.0000
18.0000 37.0000 18.0000 18.0000 18.0000 18.0000 18.0000 18.0000
18.0000 18.0000 18.0000 18.0000 18.0000 18.0000 18.0000 18.0000
18.0000 18.0000 18.0000
19.0000 39.0000 19.0000 19.0000 19.0000 19.0000 19.0000 19.0000
19.0000 19.0000 19.0000 19.0000 19.0000 19.0000 19.0000 19.0000
19.0000 19.0000 19.0000
20.0000 41.0000 20.0000 20.0000 20.0000 20.0000 20.0000 20.0000
20.0000 20.0000 20.0000 20.0000 20.0000 20.0000 20.0000 20.0000
20.0000 20.0000 20.0000
```

Only columns 1 and 2 are used for verification. Values in Column 2 are two times the value in Column 1 plus 1.

Data Set: spear3.dat

```
1.0000 4.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000
1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000
2.0000 9.0000 2.0000 2.0000 2.0000 2.0000 2.0000 2.0000 2.0000 2.0000
2.0000 2.0000 2.0000 2.0000 2.0000 2.0000 2.0000 2.0000 2.0000
```

```
3.0000 16.0000 3.0000 3.0000 3.0000 3.0000 3.0000 3.0000 3.0000 3.0000
3.0000 3.0000 3.0000 3.0000 3.0000 3.0000 3.0000 3.0000 3.0000
4.0000 25.0000 4.0000 4.0000 4.0000 4.0000 4.0000 4.0000 4.0000 4.0000
4.0000 4.0000 4.0000 4.0000 4.0000 4.0000 4.0000 4.0000 4.0000
5.0000 36.0000 5.0000 5.0000 5.0000 5.0000 5.0000 5.0000 5.0000 5.0000
5.0000 5.0000 5.0000 5.0000 5.0000 5.0000 5.0000 5.0000 5.0000
6.0000 49.0000 6.0000 6.0000 6.0000 6.0000 6.0000 6.0000 6.0000 6.0000
6.0000 6.0000 6.0000 6.0000 6.0000 6.0000 6.0000 6.0000 6.0000
7.0000 64.0000 7.0000 7.0000 7.0000 7.0000 7.0000 7.0000 7.0000 7.0000
7.0000 7.0000 7.0000 7.0000 7.0000 7.0000 7.0000 7.0000 7.0000
8.0000 81.0000 8.0000 8.0000 8.0000 8.0000 8.0000 8.0000 8.0000 8.0000
8.0000 8.0000 8.0000 8.0000 8.0000 8.0000 8.0000 8.0000 8.0000
9.0000 100.0000 9.0000 9.0000 9.0000 9.0000 9.0000 9.0000 9.0000
9.0000 9.0000 9.0000 9.0000 9.0000 9.0000 9.0000 9.0000 9.0000 9.0000
10.0000 121.0000 10.0000 10.0000 10.0000 10.0000 10.0000 10.0000
10.0000 10.0000 10.0000 10.0000 10.0000 10.0000 10.0000 10.0000
10.0000 10.0000 10.0000
11.0000 144.0000 11.0000 11.0000 11.0000 11.0000 11.0000 11.0000
11.0000 11.0000 11.0000 11.0000 11.0000 11.0000 11.0000 11.0000
11.0000 11.0000 11.0000
12.0000 169.0000 12.0000 12.0000 12.0000 12.0000 12.0000 12.0000
12.0000 12.0000 12.0000 12.0000 12.0000 12.0000 12.0000 12.0000
12.0000 12.0000 12.0000
13.0000 196.0000 13.0000 13.0000 13.0000 13.0000 13.0000 13.0000
13.0000 13.0000 13.0000 13.0000 13.0000 13.0000 13.0000 13.0000
13.0000 13.0000 13.0000
14.0000 225.0000 14.0000 14.0000 14.0000 14.0000 14.0000 14.0000
14.0000 14.0000 14.0000 14.0000 14.0000 14.0000 14.0000 14.0000
14.0000 14.0000 14.0000
15.0000 256.0000 15.0000 15.0000 15.0000 15.0000 15.0000 15.0000
15.0000 15.0000 15.0000 15.0000 15.0000 15.0000 15.0000 15.0000
15.0000 15.0000 15.0000
16.0000 289.0000 16.0000 16.0000 16.0000 16.0000 16.0000 16.0000
16.0000 16.0000 16.0000 16.0000 16.0000 16.0000 16.0000 16.0000
16.0000 16.0000 16.0000
17.0000 324.0000 17.0000 17.0000 17.0000 17.0000 17.0000 17.0000
17.0000 17.0000 17.0000 17.0000 17.0000 17.0000 17.0000 17.0000
17.0000 17.0000 17.0000
18.0000 361.0000 18.0000 18.0000 18.0000 18.0000 18.0000 18.0000
18.0000 18.0000 18.0000 18.0000 18.0000 18.0000 18.0000 18.0000
18.0000 18.0000 18.0000
19.0000 400.0000 19.0000 19.0000 19.0000 19.0000 19.0000 19.0000
19.0000 19.0000 19.0000 19.0000 19.0000 19.0000 19.0000 19.0000
19.0000 19.0000 19.0000
20.0000 441.0000 20.0000 20.0000 20.0000 20.0000 20.0000 20.0000
20.0000 20.0000 20.0000 20.0000 20.0000 20.0000 20.0000 20.0000
20.0000 20.0000 20.0000
```

Only columns 1 and 2 are used for verification. Values in Column 2 are correlated with the values in Column 1.

Data Set: spear4.dat

```
1.0000 4.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000
1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1.0000 1
2.0000 9.0000 2.0000 2.0000 2.0000 2.0000 2.0000 2.0000 2.0000 2.0000
2.0000 2.0000 2.0000 2.0000 2.0000 2.0000 2.0000 2.0000  1
3.0000 16.0000 3.0000 3.0000 3.0000 3.0000 3.0000 3.0000 3.0000 3.0000
3.0000 3.0000 3.0000 3.0000 3.0000 3.0000 3.0000 3.0000 1
4.0000 25.0000 4.0000 4.0000 4.0000 4.0000 4.0000 4.0000 4.0000 4.0000
4.0000 4.0000 4.0000 4.0000 4.0000 4.0000 4.0000 4.0000 1
5.0000 36.0000 5.0000 5.0000 5.0000 5.0000 5.0000 5.0000 5.0000 5.0000
5.0000 5.0000 5.0000 5.0000 5.0000 5.0000 5.0000 5.0000 1
6.0000 49.0000 6.0000 6.0000 6.0000 6.0000 6.0000 6.0000 6.0000 6.0000
6.0000 6.0000 6.0000 6.0000 6.0000 6.0000 6.0000 6.0000 1
7.0000 64.0000 7.0000 7.0000 7.0000 7.0000 7.0000 7.0000 7.0000 7.0000
7.0000 7.0000 7.0000 7.0000 7.0000 7.0000 7.0000 7.0000 1
8.0000 81.0000 8.0000 8.0000 8.0000 8.0000 8.0000 8.0000 8.0000 8.0000
8.0000 8.0000 8.0000 8.0000 8.0000 8.0000 8.0000 8.0000 1
9.0000 100.0000 9.0000 9.0000 9.0000 9.0000 9.0000 9.0000 9.0000
9.0000 9.0000 9.0000 9.0000 9.0000 9.0000 9.0000 9.0000 9.0000 1
10.0000 121.0000 10.0000 10.0000 10.0000 10.0000 10.0000 10.0000
10.0000 10.0000 10.0000 10.0000 10.0000 10.0000 10.0000 10.0000
10.0000 10.0000 1
11.0000 594.0000 11.0000 11.0000 11.0000 11.0000 11.0000 11.0000
11.0000 11.0000 11.0000 11.0000 11.0000 11.0000 11.0000 11.0000
11.0000 11.0000 1
12.0000 619.0000 12.0000 12.0000 12.0000 12.0000 12.0000 12.0000
12.0000 12.0000 12.0000 12.0000 12.0000 12.0000 12.0000 12.0000
12.0000 12.0000 1
13.0000 646.0000 13.0000 13.0000 13.0000 13.0000 13.0000 13.0000
13.0000 13.0000 13.0000 13.0000 13.0000 13.0000 13.0000 13.0000
13.0000 13.0000  1
14.0000 675.0000 14.0000 14.0000 14.0000 14.0000 14.0000 14.0000
14.0000 14.0000 14.0000 14.0000 14.0000 14.0000 14.0000 14.0000
14.0000 14.0000  1
15.0000 706.0000 15.0000 15.0000 15.0000 15.0000 15.0000 15.0000
15.0000 15.0000 15.0000 15.0000 15.0000 15.0000 15.0000 15.0000
15.0000 15.0000  1
16.0000 739.0000 16.0000 16.0000 16.0000 16.0000 16.0000 16.0000
16.0000 16.0000 16.0000 16.0000 16.0000 16.0000 16.0000 16.0000
16.0000 16.0000  1
17.0000 774.0000 17.0000 17.0000 17.0000 17.0000 17.0000 17.0000
17.0000 17.0000 17.0000 17.0000 17.0000 17.0000 17.0000 17.0000
17.0000 17.0000  1
18.0000 811.0000 18.0000 18.0000 18.0000 18.0000 18.0000 18.0000
18.0000 18.0000 18.0000 18.0000 18.0000 18.0000 18.0000 18.0000
18.0000 18.0000  1
19.0000 850.0000 19.0000 19.0000 19.0000 19.0000 19.0000 19.0000
19.0000 19.0000 19.0000 19.0000 19.0000 19.0000 19.0000 19.0000
19.0000 19.0000  1
```

```
20.0000 891.0000 20.0000 20.0000 20.0000 20.0000 20.0000 20.0000
20.0000 20.0000 20.0000 20.0000 20.0000 20.0000 20.0000 20.0000
20.0000 20.0000  1
```

Only columns 1 and 2 are used for verification. Values in Column 2 are correlated with the value in Column 1.

The output from the program spear using all four data sets are given below.

```
What's up Doc ?  spear

                          Data file => spear1.dat

        Column Numbers for X and Y => 1 2
  20 data read from file
    1.00000    2.00000
    2.00000    4.00000
    3.00000    6.00000
    4.00000    8.00000
    5.00000   10.00000
    6.00000    12.0000
    7.00000    14.0000
    8.00000    16.0000
    9.00000    18.0000
   10.00000    20.0000
    11.0000    22.0000
    12.0000    24.0000
    13.0000    26.0000
    14.0000    28.0000
    15.0000    30.0000
    16.0000    32.0000
    17.0000    34.0000
    18.0000    36.0000
    19.0000    38.0000
    20.0000    40.0000

Sum-Squared Difference of Ranks D =       0.0000000

Number of Standard Deviations by which D Deviates
from its Null Hypothesis Expected Value ZD =      -4.3588991

Two-Sided Significance Level of This Deviation PROBD =       0.0000131
```

```
Spearman Rank Correlation R_s =        1.0000000

Two-Sided Significance Level of This Deviation
from Zero PROBRS =        0.1111111


A small value of either PROBD or PROBRS indicates:

A SIGNIFICANT correlation (RS positive) or

A SIGNIFICANT anticorrelation (RS negative)



What's up Doc ?  spear

                          Data file => spear2.dat

         Column Numbers for X and Y => 1 2
   20 data read from file
     1.00000     3.00000
     2.00000     5.00000
     3.00000     7.00000
     4.00000     9.00000
     5.00000     11.0000
     6.00000     13.0000
     7.00000     15.0000
     8.00000     17.0000
     9.00000     19.0000
    10.00000     21.0000
     11.0000     23.0000
     12.0000     25.0000
     13.0000     27.0000
     14.0000     29.0000
     15.0000     31.0000
     16.0000     33.0000
     17.0000     35.0000
     18.0000     37.0000
     19.0000     39.0000
     20.0000     41.0000

Sum-Squared Difference of Ranks D =        0.0000000
```

```
Number of Standard Deviations by which D Deviates
from its Null Hypothesis Expected Value ZD =       -4.3588991

Two-Sided Significance Level of This Deviation PROBD =        0.0000131

Spearman Rank Correlation R_s =        1.0000000

Two-Sided Significance Level of This Deviation
from Zero PROBRS =        0.1111111


A small value of either PROBD or PROBRS indicates:

A SIGNIFICANT correlation (RS positive) or

A SIGNIFICANT anticorrelation (RS negative)



What's up Doc ?  spear

                          Data file => spear3.dat

         Column Numbers for X and Y => 1 2
   20 data read from file
     1.00000     4.00000
     2.00000     9.00000
     3.00000     16.0000
     4.00000     25.0000
     5.00000     36.0000
     6.00000     49.0000
     7.00000     64.0000
     8.00000     81.0000
     9.00000    100.0000
    10.00000     121.000
     11.0000     144.000
     12.0000     169.000
     13.0000     196.000
     14.0000     225.000
     15.0000     256.000
     16.0000     289.000
     17.0000     324.000
     18.0000     361.000
```

```
     19.0000     400.000
     20.0000     441.000


Sum-Squared Difference of Ranks D =        0.0000000


Number of Standard Deviations by which D Deviates
from its Null Hypothesis Expected Value ZD =       -4.3588991


Two-Sided Significance Level of This Deviation PROBD =        0.0000131


Spearman Rank Correlation R_s =        1.0000000


Two-Sided Significance Level of This Deviation
from Zero PROBRS =        0.1111111


A small value of either PROBD or PROBRS indicates:

A SIGNIFICANT correlation (RS positive) or

A SIGNIFICANT anticorrelation (RS negative)



What's up Doc ?  !!
spear

                          Data file => spear4.dat


         Column Numbers for X and Y => 1 2
  20 data read from file
    1.00000     4.00000
    2.00000     9.00000
    3.00000     16.0000
    4.00000     25.0000
    5.00000     36.0000
    6.00000     49.0000
    7.00000     64.0000
    8.00000     81.0000
    9.00000    100.0000
```

10.00000	121.000
11.0000	594.000
12.0000	619.000
13.0000	646.000
14.0000	675.000
15.0000	706.000
16.0000	739.000
17.0000	774.000
18.0000	811.000
19.0000	850.000
20.0000	891.000

Sum-Squared Difference of Ranks D = 0.0000000

Number of Standard Deviations by which D Deviates
from its Null Hypothesis Expected Value ZD = -4.3588991

Two-Sided Significance Level of This Deviation PROBD = 0.0000131

Spearman Rank Correlation R_s = 1.0000000

Two-Sided Significance Level of This Deviation
from Zero PROBRS = 0.1111111

A small value of either PROBD or PROBRS indicates:

A SIGNIFICANT correlation (RS positive) or

A SIGNIFICANT anticorrelation (RS negative)

REFERENCES

Press, W.H., B.P. Flannery, S.A. Teukolsky, and W.T. Vetterling. 1986. *Numerical Recipes: The Art of Scientific Computing*. Cambridge, U.K.: Cambridge University Press.

Date: 7/23/98
Sender: Amitava Ghosh <aghosh@swri.org>
To: Bruce Mabrito
Priority: Normal
Subject: Re: Second Call for Electronic Scientific Notebooks - For Se

Bruce Mabrito wrote:

> On July 1, 1998 we went out with our first call for Electronic Scientific
> Notebooks. Since then we have received several notebooks and some have been
> closed out with the latest printing.
>
> Electronic Scientific Notebooks not yet received (according to my records)
> include:
>
> Amit Armstrong 214
> 239
> 246
>
> Rui Chen 254
> 274
>
> Chuck Connor 115
> 267
>
> Randy Fedors 245
>
> Amit Ghosh 167
>
> Sitakanta Mohanty 170
>
> Stu Stothoff 163 (English, please send this message to Stu)
>
> Other Electronic Scientific Notebook holders have either turned in their
bound
> copies or submitted a memo stating they have no entries (and that note is on
> file with their earlier notebooks.
>
> If the above list is not accurate, please let me know. Please make a
concerted
> effort to print out your Electronic Scientific Notebooks and submit them for
> binding (through your Element Secretary) and get them to QA as soon as you
can.
> Bruce Mabrito x 5149

Bruce:

There was no entry for Notebook # 167 on the last quarter.

Thanks,

Amit Ghosh

RFC822.TXT

vcard.vcf

Date: 11/16/98
Sender: Amitava Ghosh
To: Bruce Mabrito
cc: Asadul Chowdhury
Priority: Normal
Receipt requested
Subject: Re:Status on Turn In/Response to Electronic Scientific Noteb

Bruce:

I guess I forgot to include SN #167 with the previous message. There was no entry to that SN also. Sorry about that.

Thanks,

Amit Ghosh

_____Reply Separator_____
Subject: Status on Turn In/Response to Electronic Scientific Notebook
Author: Bruce Mabrito
Date: 11/15/98 10:41 PM

The "call" for electronic scientific notebooks from October 1, 1998 has yielded these results to date.

Responses from: Chuck Connor (s/n # 115 turned in); Randy Fedors ("no entries" email on s/n # 245); Amit Ghosh (no entries email on s/n # 250); Britt Hill (turned in s/n # 88 pages); Sitakanta Mohanty (no entries email for s/n # 170); Roberto Pabalan (no entries email on s/n # 185 and turn in of pages on s/n # 278);
Stu Stothoff (messages passed through E Pearcy) (no entries email on s/n # 163).

Those electronic scientific "notebooks" yet to be "heard from" are:
Amit Armstrong (s/n # 214, 239, 246)
Rui Chen (s/n # 254, 274)
Chuck Connor (s/n # 267)
Amit Ghosh (s/n # 167)
Scott Painter (s/n # 282)

As always, if we have numbers incorrectly listed, please let me know. If you have no entries to report, simply so state in an email to me and we will print that note and put it in the folder for this quarter. If you have pages to turn in, please follow QAP-001 and submit only the pages and do not bind them at this time).
Many thanks. Bruce

Date: 1/21/99
Sender: Amitava Ghosh
To: Bruce Mabrito, Maria Padilla
Priority: Normal
Subject: Re:First Call for Electronic Scientific Notebook Quarterly P

Bruce:

There is no entry for Scientific Notebook #167 for the last quarter. As such, the focus of the work has changed from the original objectives significantly so that we may close this notebook and start a new one. Please let me know what to do.

Thanks,

Amit Ghosh
x3314

Reply Separator

Subject: First Call for Electronic Scientific Notebook Quarterly Prin
Author: Bruce Mabrito
Date: 1/4/99 9:35 AM

CNWRA Electronic Scientific Notebook Holders:

This is the first call for entries into CNWRA electronic scientific notebooks made from Oct. 1, 1998 through Dec. 31, 1998.

Please provide your single, unbound copy to either Maria Padilla in the Library or to me. If no entries have been made, please send to me an e-mail note to that effect that can be entered into your designated electronic scientific notebook folder. As provided by QAP-001, Scientific Notebook Control, your print outs will be bound at the end of an appropriate period (and a copy made for you) and they will be entered into the QA Archives for permanent retention. Bruce x 5149

Date: 4/19/99
Sender: Amitava Ghosh
To: Bruce Mabrito
cc: Asadul Chowdhury
Priority: Normal
Subject: Re:THIS IS NOT AN APRIL FOOL'S JOKE!

Bruce:

As requested previously, Scientific Notebook #167 should be closed. The work on that project is sporadic and probably does not merit keeping the notebook open with no entry in several quarters. If any work is done in future, we may open another notebook as the focus of the work has changed from development of the FAULTO/FAULTING module to refine the parameters, if any.

Scientific Notebook #250 did not have any entry in the last quarter. However, I expect some entries in the present quarter. Therefore, this notebook should be open.

Thanks very much.

Amit Ghosh

Reply Separator

Subject: THIS IS NOT AN APRIL FOOL'S JOKE!
Author: Bruce Mabrito
Date: 3/31/1999 6:25 PM

CNWRA Electronic Scientific Notebook Holders:

This is actually a quarterly call for print outs of your Electronic Scientific Notebooks!

In accordance with CNWRA recent tradition and Quality Assurance Procedure-001 (Scientific Notebook Control), you are to print out those entries made in your Electronic Scientific Notebooks from 1/1/99 through 3/31/99. Please provide them to either Maria or myself and we will add them to your earlier print outs. If you feel you wish to conclude/finish/close your Electronic Scientific Notebook and have it bound now, please let us know that. We also may ask you whether the quarterly print outs we now have are sufficient to have them bound into an interim book.

As always, thanks for your assistance. Bruce x 5149