1/94

KEY TECHNICAL ISSUE SENSITIVITY ANALYSIS WITH SEISMO AND FAULTO MODULES WITHIN THE TPA (VERSION 3.1.1) CODE

Prepared for

Nuclear Regulatory Commission
Contract NRC-02-97-009

Prepared by

Amitava Ghosh
John Stamatakos
Simon Hsiung
Rui Chen
Asadul H. Chowdhury
H. Lawrence McKague

Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas

February 1998

2/94

CONTENTS

Section Page

FIGURES v
TABLES vii
ACKNOWLEDGMENTS ix

1 INTRODUCTION 1-1
1.1 SCOPE AND OBJECTIVES 1-1

2 SEISMICITY 2-1
2.1 CONCEPTUAL MODEL (SEISMO) 2-1
2.1.1 SEISMO Parameters 2-3
2.1.2 SEISMO Assumptions and Abstractions 2-6
2.2 PROCEDURES 2-7
2.2.1 Parameters Considered in the Sensitivity Analyses 2-7
2.2.2 Analyses 2-9
2.3 RESULTS AND DISCUSSIONS OF SEISMO SENSITIVITY ANALYSES . . . 2-11
2.3.1 Highly Sensitive Input Parameters 2-11
2.3.2 Moderately Sensitive Input Parameters 2-11
2.3.3 Nonsensitive Input Parameters 2-11
2.4 RECOMMENDATIONS 2-11

3 FAULTING 3-1
3.1 CONCEPTUAL MODEL (FAULTO) 3-1
3.1.1 FAULTO Parameters 3-2
3.1.2 FAULTO Assumptions and Abstractions 3-3
3.2 PROCEDURES 3-5
3.2.1 Sensitivity Runs 3-5
3.2.2 Statistical Analysis 3-7
3.3 RESULTS AND DISCUSSION OF FAULTO SENSITIVITY ANALYSES . . . 3-7
3.3.1 Sensitive Input Parameters 3-7
3.3.2 Five and 20 Kilometers 3-8
3.3.3 Backfilled and Unbackfilled Drifts 3-8
3.3.4 Localized Corrosion and Uniform Corrosion 3-8
3.3.5 Effect of Fault Length 3-8
3.3.6 Effect of Fault Orientation 3-8
3.3.7 Effect of Fault Slip and Threshold Displacement 3-15
3.3.8 Cumulative Fault Displacement Rate 3-15
3.3.9 Fault Zone Width 3-15
3.3.10 Recurrence Interval 3-15
3.4 RECOMMENDATIONS 3-15
3.4.1 Recommendations for Current TPA FAULTO Module 3-15
3.4.2 Recommendations for Future Conceptual Model and Abstractions 3-18

4 REFERENCES 4-1

CONTENTS (cont'd)

APPENDIX A — SUMMARY OF RESULTS OF SENSITIVITY ANALYSES USING FAULTO MODULE

APPENDIX B — Run: FLTO_Run1, Distance to Critical Group = 5 km, Recurrence Interval = 200,000 yr, Only FAULTO, Uniform Corrosion, Backfill

APPENDIX C — Run: FLTO_Run2, Distance to Critical Group = 5 km, Recurrence Interval = 50,000 yr, Only FAULTO, Uniform Corrosion, Backfill

APPENDIX D — Run: FLTO_Run3, Distance to Critical Group = 5 km, Only SEISMO, Uniform Corrosion, Backfill

APPENDIX E — Run: FLTO_Run4, Distance to Critical Group = 5 km, Recurrence Interval = 5,000 yr, Only FAULTO, Uniform Corrosion, Backfill

APPENDIX F — Run: FLTO_Run5, Distance to Critical Group = 5 km, Recurrence Interval = 500 yr, Only FAULTO, Uniform Corrosion, Backfill

APPENDIX G — Run: FLTO_Run6, Distance to Critical Group = 20 km, Recurrence Interval = 5,000 yr, Only FAULTO, Localized Corrosion, Backfill

APPENDIX H — Run: FLTO_Run7, Distance to Critical Group = 20 km, Recurrence Interval = 200,000 yr, Only FAULTO, Localized Corrosion, Backfill

APPENDIX I — Run: FLTO_Run8, Distance to Critical Group = 20 km, Recurrence Interval = 5,000 yr, Only FAULTO, Uniform Corrosion, Backfill

APPENDIX J — Run: FLTO_Run9, Distance to Critical Group = 20 km, Recurrence Interval = 500 yr, Only FAULTO, Uniform Corrosion, Backfill

APPENDIX K — Run: FLTO_Run10, Distance to Critical Group = 5 km, Recurrence Interval = 5,000 yr, Only FAULTO, Uniform Corrosion, No Backfill

APPENDIX L — Run: FLTO_Run11, Distance to Critical Group = 20 km, Recurrence Interval = 5,000 yr, Only FAULTO, Uniform Corrosion, No Backfill

3/94

FIGURES

Figure		Page
2-1	Representative seismic hazard curves used in SEISMO sensitivity analyses	2-5
2-2	Probability diagrams showing changes in peak dose for the four highly sensitive input parameters	2-12
2-3	Probability diagrams showing changes in peak dose for the four moderately sensitive input parameters	2-13
2-4	Probability diagrams showing changes in peak dose for the three nonsensitive input parameters	2-14
3-1	Probability plot of peak total effective dose equivalent (TEDE) comparing differences in recurrence intervals for critical group at 5 and 20 km	3-9
3-2	Probability plot showing differences in dose for backfilled and unbackfilled drifts for critical group at 5 and 20 km	3-10
3-3	Probability plot showing difference in dose to a critical group at 5 km for localized and uniform corrosion	3-11
3-4a	Effect of fault zone length on waste package disruption: fault length significantly longer than proposed repository	3-12
3-4b	Effect of fault zone length on waste package disruption: fault length comparable to proposed repository	3-13
3-5	Effect of fault orientation on waste package disruption	3-14
3-6	Effect of fault zone width on waste package disruption	3-16
3-7	Probability plot showing dose to the critical group at 5 km for recurrence intervals between 500 and 50,000 yr	3-17

4/94

TABLES

Table		Page
2-1	Representative joint spacing for rock condition	2-4
2-2	Parameter values for seismic events module of iterative performance assessment	2-8
2-3	Height of yield zones for five rock conditions	2-10
2-4	Height of yield zones used in the sensitivity analysis under higher bound of seismic hazard curve	2-10
2-5	Recommended changes to the input parameters to the SEISMO code	2-16
2-6	SEISMO input parameters for base case	2-17
3-1	Parameter values for faulting events module of iterative performance assessment Phase 3	3-3
3-2	FAULTO sensitivity runs	3-6
3-3	FAULTO input parameters for base case	3-20

5/94

ACKNOWLEDGMENTS

This report was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the Nuclear Regulatory Commission (NRC) under Contract No. NRC-02-97-009. The activities reported here were performed on behalf of the NRC Office of Nuclear Material Safety and Safeguards, Division of Waste Management. The report is an independent product of the CNWRA and does not necessarily reflect the views or regulatory position of the NRC. We thank Annette Mandujano for report preparation and Barbara Long for editorial assistance. Thorough reviews by Budhi Sagar and Michael Miklas were also greatly appreciated.

QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: CNWRA-generated original data contained in this report meets quality assurance requirements described in the CNWRA Quality Assurance Manual. Sources for other data should be consulted for determining the level of quality for those data.

ANALYSES AND CODES: FAULTING Version 1.0, UDEC Version 3.0, as well as FAULTO and SEISMO (part of TPA Version 3.1.1) were used for analyses contained in this report. These computer codes are controlled under the CNWRA software configuration procedures.

6/94

1 INTRODUCTION

1.1 SCOPE AND 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 and seismicity. These potential consequences include rupture of waste package(s) (WP) directly from fault displacement or indirectly from roof collapse in unbackfilled drifts due to seismic shaking. In essence, this evaluation tests the U.S. Department of Energy (DOE) Waste Isolation and Containment Strategy hypotheses regarding potential effects of seismicity and structural deformation on WP disruption. Those hypotheses include

- 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 severity of ground motion expected in the repository horizon for tens of thousands of years will only slightly increase the amount of rockfall and drift collapse (H14)

The present study examines the sensitivity of performance of the proposed repository to input parameters in two modules of the Nuclear Regulatory Commission total system performance assessment (TPA) code Version 3.1.1. FAULTO is designed to evaluate the consequence of direct faulting of WPs and SEISMO, the consequences of seismicity induced rockfall on WPs. 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 performance to input parameters of the FAULTO and SEISMO modules was determined by the 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 SEISMO module was written specifically for the TPA Version 3.1.1. The FAULTO module was originally written as a stand-alone computer program called FAULTING Version 1.0 (Ghosh et al., 1997) but is now included with some modification in the TPA code.

7/94

2 SEISMICITY

2.1 CONCEPTUAL MODEL (SEISMO)

The SEISMO module and its adaption in the TPA Version 3.1.1 evaluates the potential for direct rupture of WPs due to rock falls induced by seismicity. The SEISMO code takes the weight of rock falls from the roof of the emplacement drifts on to the WP as input to perform impact analyses. The impact analyses involve calculation of potential loads from rock falls and assessment of the WPs ability to withstand such impact loads.

The dynamic or impact loads determined in the SEISMO module are approximated based on the principle of conservation of energy using the weights of the freely falling rocks. The impact load calculation adopts the following equation (Popov, 1970):

$$P_{dyn} = W\left(1 + \sqrt{(1 + \frac{2hk_{wp}}{W})}\right) = W\left(1 + \sqrt{1 + \frac{2h}{\Delta_{st}}}\right) \qquad (2\text{-}1)$$

where

P_{dyn} — impact load
W — weight of the rock falling
h — falling distance of rocks to WPs
Δ_{st} — spring deformation, $\Delta_{st} > o$
k_{wp} — stiffness of the WPs.

In the SEISMO module, k_{wp} is determined as unit deflection at the center of a simply supported beam when subjected to a static load at the center.

Equation (2-1) assumes

- A WP can be considered as a spring with an equivalent spring constant k_{wp}.
- No energy dissipation occurs at the point of impact from local inelastic deformation of the WP material.
- The deformation of WPs is directly proportional to the magnitude of the dynamically applied force.
- The inertia of the WP resisting an impact can be neglected.

On obtaining the impact load, the equivalent static stress resulting from the impact can be calculated by adopting a simple concept of two spheres in contact. The concept assumes pressure is distributed over a small circle of contact and the sphere representing rock has an infinite radius (Timoshenko and Goodier,

1987). From this concept it follows that the total deformation, Δ_T (both rock and WP), can be estimated by

$$\Delta_T = \left(\frac{9\pi^2}{16} \frac{P_{dyn}^2 (K_{wp} + K_{rock})^2}{R_{wp}} \right)^{\frac{1}{3}} \tag{2-2}$$

where

R_{wp} — radius of lower sphere or WP
K_{wp} — material constant for lower sphere or WP
K_{rock} — material constant for upper sphere or rock fall

$$K_{wp} = \frac{1 - \mu_{wp}^2}{\pi E_{wp}} \tag{2-3}$$

$$K_{rock} = \frac{1 - \mu_{rock}^2}{\pi E_{rock}} \tag{2-4}$$

where

E_{wp} — modulus of elasticity of lower sphere or WP
μ_{wp} — Poisson's ratio of lower sphere or WP
E_{rock} — modulus of elasticity of upper sphere or rock fall
μ_{rock} — Poisson's ratio of upper sphere or rock fall

The impact stress, p can be obtained by

$$p = \frac{3}{2\pi} \left(\frac{16 P_{dyn}}{9\pi^2} \frac{1}{(K_{wp} + K_{rock})^2 R_{wp}^2} \right)^{\frac{1}{3}} \tag{2-5}$$

Equation (2-5) is used in the SEISMO module to estimate impact stress on WPs. The impact stress is then compared with the ultimate material strength of the WPs to assess WP integrity.

The supports for WPs are treated as flexible in the SEISMO module. In the current conceptual design, a WP will be sitting on four equally spaced v-shaped thin beams with one vertical cylindrical bar on either side of the v-shaped beam. In the SEISMO module, only the supports at both ends of a WP are considered. Originally, Δ_{st} in Eq. (2-1) was the static deflection of the object impacted. To account for the deformability of WP support, Δ_{st} is made to be equal to

$$\Delta_{st} = \frac{W}{k_{wp}} + \frac{W}{N_{wp} N_p k_{supports}} \tag{2-5a}$$

where k_{wp} is the stiffness of the WP, N_{wp} is 2 (the number of supports at the end of a WP), N_{wp} is the number of support points at one end, and $k_{supports}$ is the stiffness of the vertical bars.

k_{wp} and $k_{supports}$ can be calculated by

$$k_{supports} = \frac{AE_{supports}}{L_b} \tag{2-5b}$$

and

$$k_{wp} = \frac{48EI}{L_{wp}^3} \tag{2-5c}$$

where A is the cross-sectional area and L_b is the height of the vertical bar.

Design of shape and dimension of the bar is currently not available. In the SEISMO module, the bar is assumed to be cylindrical in shape with a radius of 0.0508 m and a height of 0.3048 m. $E_{supports}$ is the Young's modulus of the vertical bar or WP (206,896.55 MPa), L_{wp} is the length of the WP, and I is equal to $\pi R_{ave}^3 t$. t is the thickness of WP (0.12m) and R_{ave} is the average thickness of the outer and inner wall radius of the WP.

2.1.1 SEISMO Parameters

The input parameters used in SEISMO are contained in two data files: *seismo.dat* and *tpa.inp*. Data file *seismo.dat* includes information regarding the extent of rock fall (expressed in terms of thickness of yield zone in the rock) and the rest of parameters are included in *tpa.inp* file.

Joint Spacing and Rock Categories in TSw2 Unit

Not all rocks falling from the roof of the emplacement drifts will have an effect on WPs. The effective size of the fallen rock that may impact WPs is assumed to be controlled by joint spacing (JS). JSs in the TSw2 thermomechanical unit cover a range of JS distributions. They are represented by five distinct rock condition categories in SEISMO. The rock conditions are estimated using available JS information for the TSw2 unit (Brechtel et al., 1995). This JS information is used in the SEISMO module to determine the volume of rock fall that will impact WPs. JS information is presented in terms of rating of JS (Hoek and Brown, 1982). Three JS ratings are observed in the TSw2 Unit: 5, 8, and 10. JS-rating of 5 indicates a JS that is smaller than 0.06 m; 8 is for JS between 0.06 to 0.2 m; and 10 represents JS of 0.2 to 0.6 m. For the rock condition scheme used in SEISMO, condition 5 is assumed equivalent to rock with a JS rating of 5; condition 4 is assumed equivalent to rocks with a JS rating of 8. Rocks related to JS rating of 10 are divided into three conditions: 1, 2, and 3. This subdivision is reasonable because (i) the range for JS rating of 10 between 0.2 to 0.6 m is large and (ii) larger JS will induce greater impact on WPs.

To implement the rock conditions in the SEISMO module, representative JSs were selected by Center for Nuclear Waste Regulatory Analyses (CNWRA) staff so that the effective volume of falling

rock that will impact WPs can be directly calculated (table 2-1). These representative values are treated as average values for each rock category.

Table 2-1. Representative joint spacing for rock condition

Rock Condition	Representative Joint Spacing, m	Estimated Percent of Representative Joint Spacing in Repository*
1	0.53	0.5
2	0.40	0.5
3	0.27	0.5
4	0.13	62.9
5	0.03	35.6

*Estimated from Brechtel et al. (1995).

Fractional Coverage of Rock Conditions

Based on Brechtel et al. (1995) rock condition 4 appears to contain the largest portion of the repository horizon bedrock, the lithophysae-poor Topopah Spring Formation (TSw2). About 62.9 percent of the repository area can be characterized as rock condition 4. Rock condition 5 occupies roughly 35.6 percent of the area. Rock conditions 1, 2, and 3 take up only 1.5 percent of the area in approximately equal proportions.

Seismic Hazard Parameters

SEISMO uses representative seismic hazard curves as input to estimate the level of groundshaking in the emplacement drifts. For a given seismic hazard curve, the return periods for four levels of ground motion (usually 0.2, 0.4, 0.6, and 0.8 g) are abstracted and used by the Iterative Performance Assessment Executive Sampler to generate a history of seismic events. Inherent in the seismic hazard curve abstraction are assumptions about the degree of attenuation of ground motion from the surface to the subsurface. In the present study, attenuation factors between 1.0 (no attenuation) and 0.5 (50 percent attenuation) were used. An attenuation factor of 0.5 was applied for the base case runs.

In the base case, the hazard curve, developed for the Exploratory Studies Facility (ESF) Design Study and summarized in Wong, et al. (1995, figure 5, page 59, derived from the U.S. Department of Energy, 1995), was used. For runs designed to test the sensitivity of the level of ground shaking, two additional seismic hazard curves (figure 2-1a) were generated based on upper and lower bounds of faulting activity rates from the paleoseismic and geodetic records (U.S. Geologic Survey, 1996, table 4.2.1; Ferrill et al., pages 4-1 to 4-15, 1996). Details of those upper and lower bounding hazard curves will be forthcoming in an FY98 deliverable. Ground motion attenuation for these hazard curves is based on the functions of Abrahamson and Silva (1997) and Sadigh et al. (1997). The seismic recurrence sampling is handled by the SAMPLER utility module in the TPA Version 3.1.1 and the

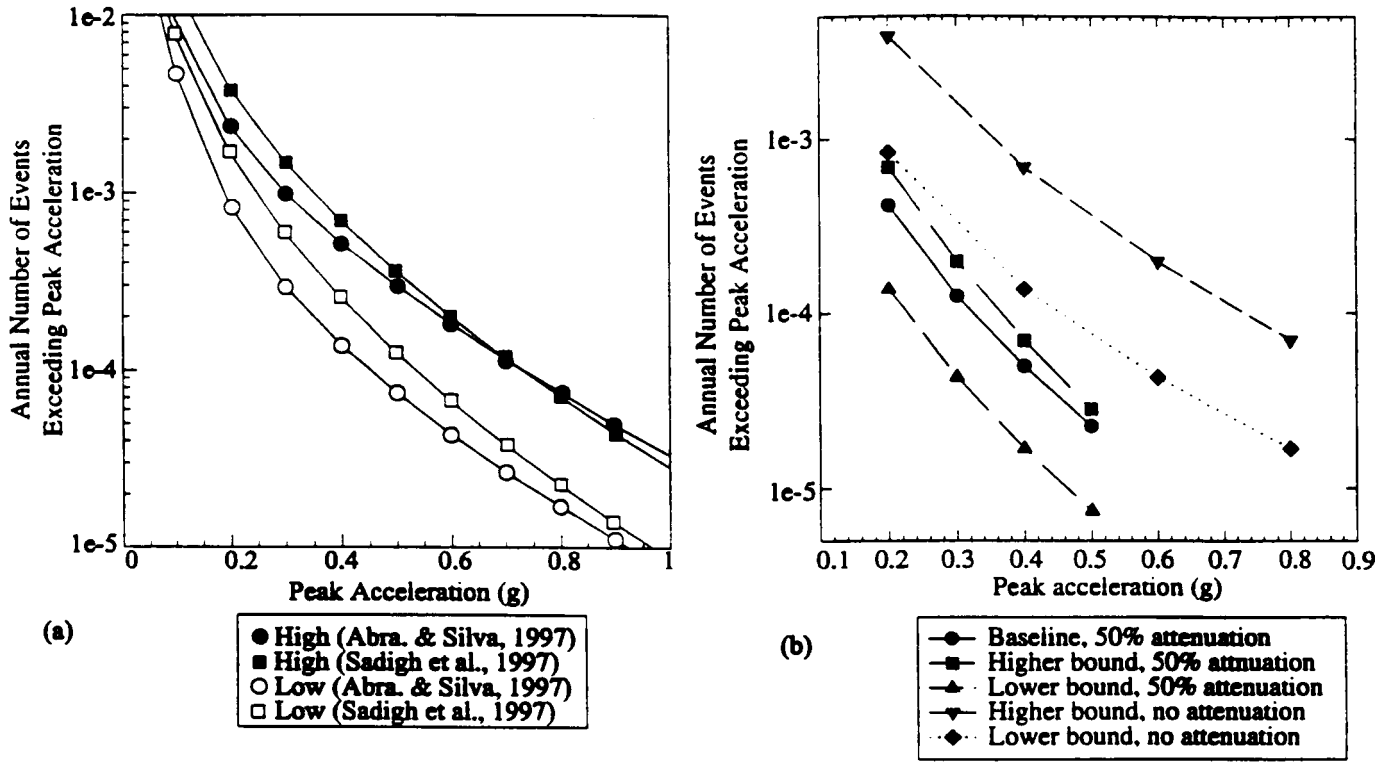


Figure 2-1. Representative seismic hazard curves used in SEISMO sensitivity analyses. (a) Peak ground motion plotted as a function of return period for lower and upper bound hazard levels using two alternative attenuation relationships. (b) Peak ground motion accelerations abstracted from seismic hazard curves. Four values derived from each curve as input to the SEISMO module.

sampling points (accelerations) are provided in the *tpa.inp* file. Four discrete sampling accelerations are selected for the SEISMO module. For the base case these accelerations are 0.1, 0.2, 0.3, and 0.4g (equivalent to 0.2, 0.4, 0.6, and 0.8 (figure 2-1b) on the seismic hazard curve assuming 50 percent reduction of acceleration in the subsurface). The recurrence time associated with each acceleration is 500, 2,400, 8,000, and 20,000 yr.

Input Parameters for TSw2 Unit and Waste Packages

The following parameters for TSw2 unit and WPs are used in the SEISMO module. Values associated with each parameter are estimated mean values. Most values for parameters related to WPs are assumed based on the best judgment while those for TSw2 unit are estimated from Brechtel et al. (1995).

WPStiffnessforSEISMO[Pa×m] = 1.2097×10^{9}
WPModulusofElasticityforSEISMO[Pa] = 2.069×10^{11}
WPPoissonRatioforSEISMO[unitless] = 0.2

RockModulusOfElasticityforSEISMO[Pa] = 3.44828×10^{10}
RockPoissonRatioforSEISMO[unitless] = 0.2
RockFallingDistanceforSEISMO[m] = 2.0
WPFallingDistanceforSEISMO[m] = 0.3
WPSupportStiffnessforSEISMO[Pa×m] = 5.5×10^{9}
WPNumberofSupportPairforSEISMO = 2
WPUltimateStrength[N/m^2] = 1.37931×10^{9}

2.1.2 SEISMO Assumptions and Abstractions

The following assumptions are made to use the impact (dynamic) load calculation as outlined in Eq. (2-1):

- A WP is treated as a simply supported beam.
- No energy dissipation takes place at the point of impact owing to local inelastic deformation of the WP material.
- The deformation of WPs is directly proportional to the magnitude of the dynamically applied force.
- The inertia of the WP resisting an impact may be neglected.
- The WP is spherical in shape instead of cylindrical.
- The WP is disrupted once the ultimate material strength of the WP is reached.
- There is no link between seismicity and corrosion.
- All WPs under one rock condition are assumed to be disrupted at the same time if the impact stress of falling rock on WPs owing to a particular earthquake condition exceeds the ultimate material strength of the WPs.
- Falling rocks have infinite strength (i.e., all energy generated through dynamic impact is transferred to WP).
- The thickness of yield zone, estimated from numerical modeling results using the UDEC computer code, is assumed to be the height of rock that will contribute to impact stress calculation. The other dimensions are controlled by JS.
- The emplaced drifts are not backfilled.
- The WPs do not lose strength as they corrode. WP strength is assumed constant throughout the period of interest.

Most of these assumptions and abstractions are conservative owing to the following

- The dynamic load obtained from Eq. (2-1) is higher than expected given the problems under consideration because the ratio of h/Δ_{st} is large. When the ratio is high, Eq. (2-1) is only approximately true.

- The assumption that a WP can be treated in the calculations as a sphere gives a relatively higher impact stress than other more likely WP geometries because the contact area calculated using this assumption is smaller.

- The failure criterion used for assessing disruption of a WP does not account for plastic deformation. Metal objects like the WPs would probably sustain some level of plastic deformation without failure.

- All rocks under one rock condition are assumed to fall at the same time in response to a given level of ground shaking. If the calculated impact stress exceeds the ultimate strength of WPs, all the WPs beneath a drift roof with that rock condition are assumed to be disrupted. In reality, a fraction of the rock under that rock condition may fall owing to a seismic event because of the inherent variations in rock type characteristics.

- The effective stress on a WP from a falling rock will be less if the rock is allowed to break at impact.

- Backfilling of the emplacement drifts will mitigate the effects of seismicity.

One nonconservative assumption is that WPs will not lose strength as they corrode. In reality, WPs should lose strength with time as corrosion takes place.

2.2 PROCEDURES

2.2.1 Parameters Considered in the Sensitivity Analyses

Parameters investigated in the SEISMO module sensitivity analyses are provided in table 2-2. These parameters were originally coded as constants requiring that each parameter be changed one at a time in each sensitivity case (run). All runs were made using 20,000 yr period of interest with a critical group at 5 km. For most parameters, variations used in the sensitivity analyses were based on engineering judgment of the expected normal variations of these parameters. Parameter variations for seismicity were based on lower and upper bound seismic hazard curves described briefly in section 2.1.2.

Table 2-2. Parameters in SEISMO module studied for total performance assessment sensitivity analysis

Case No.	Parameter Evaluated	Mean Value	Parameter Variation
1	Young's Modulus of TSw2	3.448×10^{10} Pa	+20% of mean value
2			-20% of mean value
3	Ultimate Strength of Waste Packages	1.37931×10^{9} Pa	+20% of mean value
4			-20% of mean value
5	Poisson's Ratio of TSw2	0.2	+25% of mean value
6			-25% of mean value
7	Stiffness of Waste Packages	1.2097×10^{10} Pa*m	+20% of mean value
8			-20% of mean value
9	Joint Spacing	0.53, 0.4, 0.27, 0.13, 0.03 m	Higher bound 0.6, 0.466, 0.333, 0.2, 0.06 m
10			Lower bound 0.466, 0.333, 0.2, 0.06, 0.03 m
11	Young's Modulus of Waste Package Material	2.069×10^{11} Pa	+10% of mean value
12			-10% of mean value
13	Poisson's Ratio of Waste Package Material	0.2	+25% of mean value
14			-25% of mean value
15	Stiffness of Supports to Waste Package	5.5×10^{9} Pa*m	+20% of mean value
16			-20% of mean value
17	Hazard Curve (No attenuation with depth)	0.2g 2,400yr 0.3g 8,000yr 0.4g 20,000yr 0.5g 44,000yr (50% attenuation)	Higher bound* 0.2g 261yr 0.4g 1,451yr 0.6g 5,045yr 0.8g 14,186yr
18			Lower bound* 0.2g 1,196yr 0.4g 7,273yr 0.6g 23,223yr 0.8g 59,312yr

11/94

Table 2-2. Parameters in SEISMO module studied for total performance assessment sensitivity analysis (cont'd)

Case No.	Parameter Evaluated	Mean Value	Parameter Variation
19	Hazard Curve (50% attenuation)		Higher bound* 0.2g 1,451yr 0.3g 5,045yr 0.4g 14,186yr 0.5g 35,184yr
20			Lower bound* 0.2g 7,273yr 0.3g 23,223yr 0.4g 59,312yr 0.5g 135,208yr
21	Hazard Curve (No attenuation with depth)		Higher bound* Corrosion On
22			Higher bound* Localized Corrosion Off & No Backfill
23	Distribution of five Rock Conditions in TSw2	Rock Condition 1 0.005 Rock Condition 2 0.005 Rock Condition 3 0.005 Rock Condition 4 62.9 Rock Condition 5 35.6	1 0.005 2 0.15 3 0.15 4 0.339 5 0.356
*	Hazard curves determined based on attenuation functions of Abrahamson and Silva (1997) and Sadigh et al. (1997)		

2.2.2 Analyses

To test sensitivity of repository performance to SEISMO parameters, peak dose values from the *gwpkdos.res* file were used to construct probability diagrams. In SEISMO, each parameter was coded as a constant (i.e., these parameters are not sampled) thereby requiring a parameter-by-parameter sensitivity study. Thus, the input parameters were not statistically ranked by either a multivariant linear or nonparametric rank correlation (as was done for the parameters in the FAULTO study). Instead, parameter sensitivity was determined by the effect on peak dose for the lower, middle, and higher bound values. The number of WP failures was not examined because WP failures are simply discretized into three values (32, 64, or 4,086) depending on whether rock conditions 1, 2, and 4 failed. The underlying assumption is that once rocks of a given rock condition fail, all WPs housed in that rock condition are impacted. If the conditions of that fall are right for WP failure, all WPs housed in that rock condition will also fail. Rock condition 5, under present model conditions, does not yield rockfalls capable of generating WP failure.

During the sensitivity analyses, peak doses (from the *gwpkdos.res* file) were examined. To simulate 20,000 yr time period, the seismic hazard curve input was modified to include a higher ground acceleration since the original input for seismic hazard proposed as mean values was for 10,000 yr. The height of yield zone in the rock was also adjusted to reflect such a modification since higher ground acceleration could induce higher yield zone. Except for rock condition 5, the height of the yield zone for some rock conditions was adjusted downward from the mean values to increase sensitivity. The heights of yield zones for each rock condition subjected to ground accelerations are given in table 2-3.

Table 2-3. Height of yield zones for five rock conditions

Ground Acceleration, g	Height of Yield Zone, m				
	Rock Condition				
	1	2	3	4	5
0.2	0.0	1.2	3.0	6.5	10.00
0.3	0.0	1.4	4.0	7.5	11.33
0.4	0.0	1.5	5.0	8.5	12.66
0.5	0.0	1.7	6.0	9.5	13.99

For higher bound of hazard curve input, the height of yield zones for five rock conditions and associated ground accelerations are given in table 2-4.

Table 2-4. Height of yield zones used in the sensitivity analysis under higher bound of seismic hazard curve

Ground Acceleration, g	Height of Yield Zone, m				
	Rock Condition				
	1	2	3	4	5
0.2	0	1.2	3.0	6.5	10.00
0.4	0	1.5	5.0	8.5	12.66
0.6	0.5	2.0	7.0	10.5	15.99
0.8	1.2	3.3	10.0	14.0	22.0

12/94

Throughout the sensitivity study, the entire repository was treated as one subarea assuming uniform corrosion with the exception of one case where corrosion was included. Corrosion values were adjusted by setting the oxygen partial pressure value to low value (no localized corrosion) or at the recommended base case value. Uniform corrosion was omitted from most sensitivity analysis runs to allow efficient testing of the SEISMO input parameters. The relative importance of the two parameters can be examined in the TSPA production runs.

2.3 RESULTS AND DISCUSSIONS OF SEISMO SENSITIVITY ANALYSES

From the probability diagrams, three categories of parameter sensitivity were defined: highly sensitive, moderately sensitive, and not sensitive. The distinctions between the three categories are based on the overall change in peak dose resulting from the change in the parameter value. Highly sensitive parameters show a greater than tenfold increase in peak dose over the sampled parameter range. Moderately sensitive parameters show a two to ten-fold increase in peak doses over the sampled input parameter range. Not sensitive parameters showed no significant change in peak doses over the sampled input parameter range.

2.3.1 Highly Sensitive Input Parameters

Peak dose is highly sensitive to four SEISMO input parameters: Young's Modulus of TSw2 Lithology, Ultimate Strength of WPs, Joint Spacing of the TSw2 Lithology, and the degree of surface-to-subsurface attenuation of ground motions. Summary probability diagrams of peak dose for these input parameters are given in figure 2-2.

2.3.2 Moderately Sensitive Input Parameters

Peak dose is moderately sensitive to three SEISMO input parameters: Poisson's Ratio of TSw2 Lithology, Stiffness of WPs, and different estimates of the seismic hazard. Summary probability diagrams of peak dose for these input parameters are given in figure 2-3.

2.3.3 Nonsensitive Input Parameters

Peak dose is not sensitive to three SEISMO input parameters: Young's Modulus of WPs, Poisson's Ratio of WPs, and Stiffness of WPs Supports. Summary probability diagrams of peak dose for these input parameters are given in figure 2-4.

2.4 RECOMMENDATIONS

Given the ranking provided in the preceding section, the following parameters should be changed from constants to variables because they may have significant effects on ground water peak dose:

- Young's Modulus of TSw2
- Ultimate Strength of WPs
- JS of TSw2

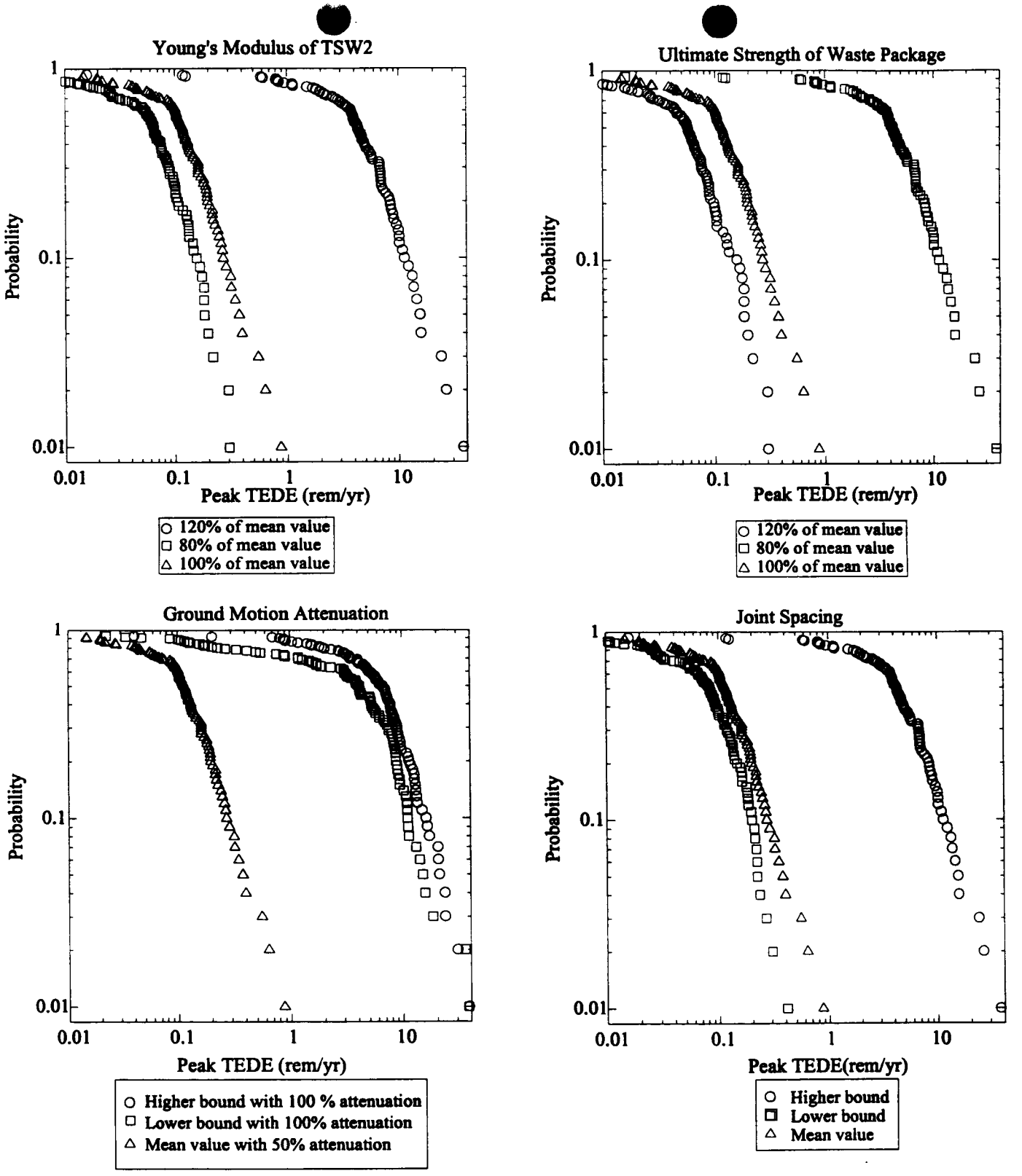


Figure 2-2. Probability diagrams showing changes in peak dose for the four highly sensitive input parameters

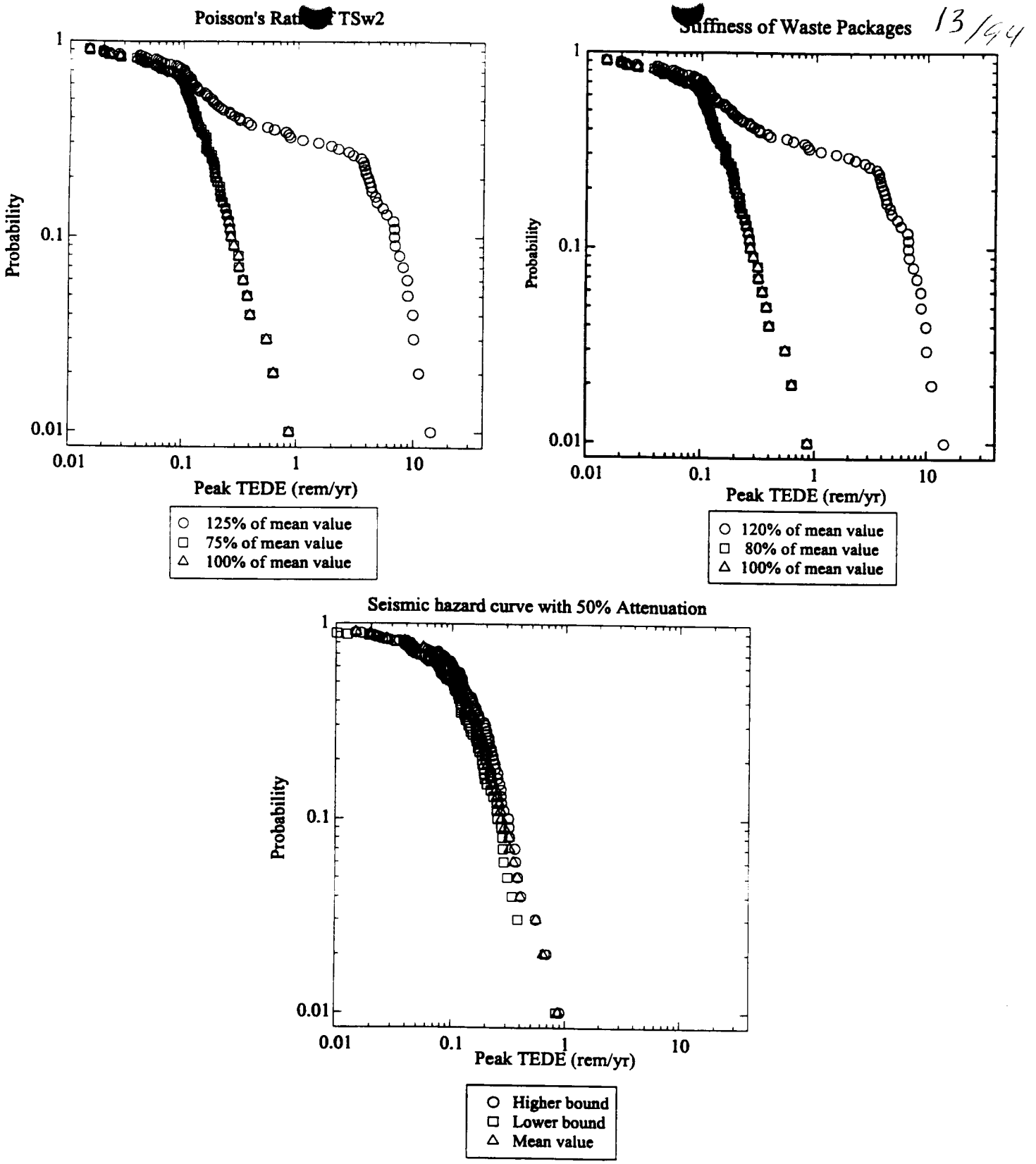


Figure 2-3. Probability diagrams showing changes in peak dose for the three moderately sensitive input parameters

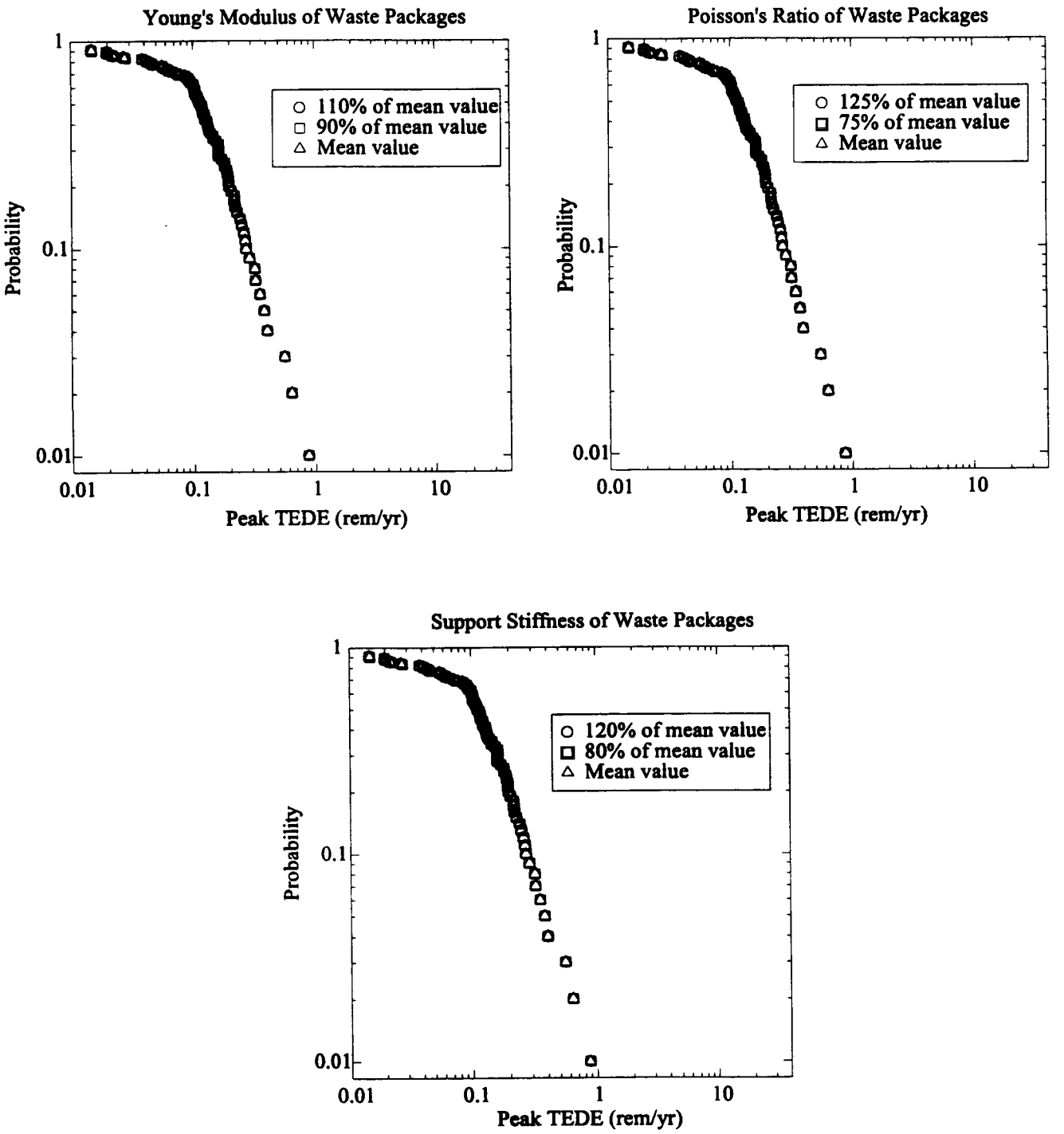


Figure 2-4. Probability diagrams showing changes in peak dose for the three nonsensitive input parameters

- Poisson's Ratio of TSw2
- Fraction coverage of each rock condition in TSw2
- Attenuation factor of peak ground motions from the surface in the subsurface

Changing these parameters to variables will allow better evaluation of sensitivity in the total system sensitivity analysis. To make fractional coverage of each rock condition in TSw2 parameter a variable, some modifications in SEISMO module will be necessary. The extent of the modifications, however, should be minimal. It is possible these modifications can be accomplished in time for the production runs of the total system performance. To make "surface/depth attenuation" parameter a variable will require some modifications in the utility modules related to the generation of time and magnitude of seismic events. The level of effort required for such modification is not known. For the total system sensitivity analysis to be performed at this time, the "surface/depth attenuation" parameter may be treated as a constant and sensitivity studied by varying the value of the parameter with each run. Barring that possibility, an attenuation factor of 0.5 is recommended for the base case runs and a factor of 1.0 for bounding analyses.

As discussed earlier, the current SEISMO module assumes that rock under one rock condition will fall at the same time when responding to a particular earthquake. This assumption leads to a conservative estimate of peak dose for those earthquakes. The level of conservatism can be reduced by treating the amount of rock fall as probability density functions (PDFs). Defining that PDF requires additional analyses of available joint and fracture data.

The height of yield zones for the five rock conditions under various ground accelerations were assumed based on the results of three limited case studies for stability of emplacement drifts under heated and seismic conditions using UDEC computer code. The reasonableness of these assumptions need to be verified by additional numerical and field-based investigations.

The SEISMO code should also be modified to allow peak ground motions from the seismic hazard curves to be sampled as PDFs. This modification would allow a more complete sampling of variations in the seismic hazards at YM.

The current conceptual model implemented in the SEISMO code, in general, is very conservative. New conceptual model or abstraction may be developed in two ways. The first approach is to develop an empirical expression for definition of WP failure using numerical modeling technique. In this approach, energy consumption due to WP and rock deformation can be factored into the model. The second approach is to modify the current conceptual model to include potential energy loss as a result of plastic deformation of WPs and rock breaking upon impact.

For the production run, the changes shown in table 2-5 are recommended.

Based on these results, the SEISMO input parameters recommended for the production runs of the code are given in table 2-6. Details about the bounding values and distributions are given in the notes following the table.

Table 2-5. Recommended changes to SEISMO input parameters

	Current Values		Recommended Changes	
Parameter	**Distribution**	**Value**	**Distribution**	**Values**
RockModulusOfElasticityfor SEISMO[PA]	Constant	3.448D10	Normal	2.75[illegible]10 4.13[illegible]D10
RockPoissonRatiofor SEISMO[]	Constant	0.2D0	Normal	0.15[illegible]D0 0.250D0
SEISMOJointSpacing1[m]	Constant	0.53D0	Normal	0.466D0 0.600D0
SEISMOJointSpacing2[m]	Constant	0.40D0	Normal	0.333D0 0.466D0
SEISMOJointSpacing3[m]	Constant	0.27D0	Normal	0.200D0 0.333D0
SEISMOJointSpacing4[m]	Constant	0.13D0	Normal	0.060D0 0.200D0
SEISMOJointSpacing5[m]	Constant	0.03D0	Normal	0.030D0 0.060D0
WPUltimateStrength[N/m^2]	Constant	1.37931D09	Normal	1.103448D09 1.655172D09

Table 2-6. SEISMO input parameters for base case

Parameter Type	Input Parameter	Comment	Range	Reference
hazardcurve	SeismicHazardCurveforSEISMO	Minimum peak acceleration for bins, return period (yr); number of magnitudes for recurrence of seismic events, magnitude, and recurrence time	4 0.1 500.0 0.2 2400.0 0.3 8000.0 0.4 20000.0	Wong et al. (1995), figure 5, page 59
constant	WeightPercentageOfRockFallThatHitsWPforSEISMO[1]	Weight percentage of rock fall that hits WP	1.0	Not used
constant	WeightOfWPforSEISMO[N][2]	Weight of WP used in impact calculation during free fall (N)	1.27D05	Not used
constant	WPStiffnessforSEISMO[Pa*m][3]	WP stiffness used for rockfall impact calculation (Pa-m)	1.2097D10	CNWRA staff best estimate
constant	WPModulusOfElasticityforSEISMO[Pa][4]	WP modulus of elasticity (Pa)	2.069D11	Popov (1970)
normal	RockModulusOfElasticityforSEISMO[Pa][5]	Rock modulus of elasticity (Pa)	2.7584D10 4.1376D10	Brechtel et al. (1995), table 2-4
constant	WPPoissonRatioforSEISMO[][6]	WP Poisson Ratio	0.2D0	Popov (1970)
normal	RockPoissonRatioforSEISMO[][7]	Rock Poisson Ratio	0.15D0 0.25D0	Brechtel, et al. (1995), table 2-4
constant	RockFallingDistanceforSEISMO[m][8]	Rock falling distance gap between top of WP and drift crown (m)	2.0D0	CNWRA staff best estimate
constant	WPFallingDistanceforSEISMO[m][9]	WP falling distance for freefall calculations (m)	0.3D0	Not used
constant	WPNumberofSupportPairforSEISMO[10]	Number of support pairs on WP pedestal	2	CNWRA staff best estimate
constant	WPSupportStiffnessforSEISMO[pa*m][11]	Stiffness of pedestal	5.5D09	CNWRA staff best estimate
constant	DistributionJointSpacing1forSEISMO[12]	Fractional areal coverage for rock condition 1	5.0D-03	CNWRA staff best estimate
constant	DistributionJointSpacing2forSEISMO[12]	Fractional areal coverage for rock condition 2	5.0D-03	CNWRA staff best estimate
constant	DistributionJointSpacing3forSEISMO[12]	Fractional areal coverage for rock condition 3	5.0D-03	CNWRA staff best estimate
constant	DistributionJointSpacing4forSEISMO[12]	Fractional areal coverage for rock condition 4	0.629D0	CNWRA staff best estimate
constant	DistributionJointSpacing5forSEISMO[12]	Fractional areal coverage for rock condition 5	0.356D0	CNWRA staff best estimate

Table 2-6. SEISMO input parameters for base case (cont'd)

Parameter Type	Input Parameter	Comment	Range	Reference
normal	SEISMOJointSpacing1[m][13]	Joint spacing for rock condition 1	0.466D0 0.600D0	Brechtel et al. (1995)
normal	SEISMOJointSpacing2[m][13]	Joint spacing for rock condition 2	0.33D0 0.466D0	Brechtel et al. (1995)
normal	SEISMOJointSpacing3[m][13]	Joint spacing for rock condition 3	0.20D0 0.333D0	Brechtel et al. (1995)
normal	SEISMOJointSpacing4[m][13]	Joint spacing for rock condition 4	0.06D0 0.20D0	Brechtel et al. (1995)
normal	SEISMOJointSpacing5[m][13]	Joint spacing for rock condition 5	0.03D0 0.06D0	Brechtel et al. (1995)
normal	WPUltimateStrength[N/m^2][14]	Ultimate strength of WP	1.103448D09 1.655172D09	Popov (1970) Assumed based on the strength of SS carbon steel (3.5% Ni and 0.4% C)
constant	GrainDensityforTSw2SEISMO[g/cm^3][15]	Grain density for TSw2	2.55	Brechtel et al. (1995)

Notes:

[1]**WeightPercentageOfRockFallThatHitsWPforSEISMO**
This parameter is not currently used in WP failure calculation.

[2]**WeightOfWPforSEISMO[N]**
This parameter is not currently used in WP failure calculation.

[3]**WPStiffnessforSEISMO[Pa*m]**
This parameter assuming a simple supported beam with load applied at the center of the beam and its value is estimated based on the following equation:

$$K_{wp} = \frac{48EI}{L^3}$$

where K_{wp} — stiffness of the WPs

I — $\pi R_{ave}^3 t$, R_{ave} is the average of inner and outer radius of the WPs and t is the thickness of the WPs

Table 2-6. SEISMO input parameters for base case (cont'd)

E — Young's modulus of the WPs

L — length of the WPs.

R_{ave} — (0.9 + 0.78) / 2 = 0.84 m

t — 0.12 m

L — 5.682 m

(Note: t and L are obtained from the Reference Data Set)

[4]PModulusOfElasticityforSEISMO[Pa]

The value of this parameter is extracted directly from the Appendix Table 1, p. 423, Popov (1970).

[5]RockModulusOfElasticityforSEISMO[Pa]

The mean value for the parameter is obtained from table 2-4, p. 2–12, SANDIA report, Geotechnical Characterization of the North Ramp of the Exploratory Studies Facility, Volume I of II Data Summary, SAND95–0488/1 (Brechtel et al., 1995). The 20% variation for the assumed normal distribution of this parameter is adopted from table 5.1, p. 5–19, DOE Site Characterization Plan.

[6]WPPoissonRatioforSEISMO[]

The value of this parameter is obtained directly from p. 36, Popov (1970).

[7]RockPoissonRatioforSEISMO[]

The mean value for the parameter is obtained from table 2-4, p. 2–12, SANDIA report, Geotechnical Characterization of the North Ramp of the Exploratory Studies Facility, Volume I of II Data Summary, SAND95–0488/1 (Brechtel, et al., 1995). The 25% variation for the assumed normal distribution of this parameter is adopted from table 5.1, p. 5–19, DOE Site Characterization Plan.

[8]RockFallingDistanceforSEISMO[m]

This parameter is estimated as follows

RockFallingDistanceforSEISMO[m] =

diameter of emplacement drift (currently 5 m) − diameter of the WPs (about 1.8 m) − height of pedestal (assumed to be 1.2 m with no reference basis)

[9]WPFallingDistanceforSEISMO[m]

This parameter is not currently used in WP failure calculation; this parameter cannot be removed.

[10]WPNumberofSupportPairforSEISMO

The conceptual SEISMO module is based on an assumption that WPs are simply support beams. Consequently, two support beams are assumed.

16/54

Table 2-6. SEISMO input parameters for base case (cont'd)

[11]WPSupportStiffnessforSEISMO[pa*m]

The support stiffness can be obtained using the following equation

$$k_{support} = \frac{AE_{support}}{L_b}$$

where $K_{support}$ — support stiffness

A — cross-sectional area of the support (currently assuming radius of the cross section is 0.0508 m with no reference basis)

$E_{support}$ — Young's Modulus of the support assuming to be equal to the that of WPs

L_b — height of support (assumed to be 0.3048 m).

[12]SEISMOJointSpacing1[m]
[12]SEISMOJointSpacing2[m]
[12]SEISMOJointSpacing3[m]
[12]SEISMOJointSpacing4[m]
[12]SEISMOJointSpacing5[m]

Not all rocks falling from the roof of the emplacement drifts will impact WPs. The effective size of the rock that impacts WPs will be controlled by JS. For abstraction into the TPA code, the TSw2 thermomechanical unit was subdivided into five distinct rock conditions. The rock conditions are estimated using available JS (Brechtel et al., 1995) information for the TSw2 provided in a SANDIA report (Brechtel et al., 1995) that summarizes data collected from NRG holes. In the report, the JS information is presented in terms of rating of JS (Hoek and Brown, 1982). Three JS ratings are observed in the TSw2 Unit: 5, 8, and 10. Rating of 5 indicates a JS that is smaller than 0.06 m; 8 is for JS between 0.06 to 0.2 m; 10 represents JS of 0.2 to 0.6 m. For the rock condition scheme used in the SEISMO module, condition 5 is assumed to be equivalent to the rocks with JS rating of 5; condition 4 is assumed to be the rocks with JS rating of 8; and rocks related to JS rating of 10 are further subdivided into three conditions: 1, 2, and 3. This subdivision is considered reasonable because (i) the range for JS rating of 10 between 0.2 to 0.6 m is large and (ii) larger JS will induce greater impact on WPs.

A normal distribution of JS is assumed in each rock condition category because no additional information about the distributions of JSs was compiled when the SEISMO module was coded. Future work will examine the validity of this assumption.

[13]DistributionJointSpacing1forSEISMO
[13]DistributionJointSpacing2forSEISMO
[13]DistributionJointSpacing3forSEISMO
[13]DistributionJointSpacing4forSEISMO
[13]DistributionJointSpacing5forSEISMO

Based on the SANDIA report (Brechtel et al., 1995), rock condition 4 appears to contain a disproportionally larger volume of the TSw2 unit. About 62.9% of the repository can be characterized as rock condition 4. Rock condition 5 occupies roughly 35.6% of the repository. Rock conditions 1, 2, and 3 take up only 1.5% of the area and are equally subdivided into 0.5 % of the repository.

[14]WPUltimateStrength[N/m^2]

The mean value of this parameter is obtained from the appendix table 1, p. 423, Popov (1970). The 20% variation for the assumed normal distribution is ba[illegible] the expert judgment of the authors.

[15]GrainDensityforTSw2SEISMO[]

The value for the parameter is obtained from table 2-4, p. 2-12, SANDIA report, Geotechnical Characterization of the North Ramp of the Exploratory Studies Facility, Volume I of II Data Summary, SAND95-0488/1.

17/94

3 FAULTING

3.1 CONCEPTUAL MODEL (FAULTO)

The stand-alone faulting module FAULTING and its adaptation in the TPA Version 3.1.1 FAULTO evaluates the potential for direct WP 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 (e.g., length, width, orientation, and displacement) as well as overall fault recurrence intervals are samples from a series of probability distribution functions derived from geological observations of faults at YM (e.g., U.S. Geologic Survey, 1996).

In the 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 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 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 statistically significant assessment of potential consequences.

In the modified version of FAULTING code used in the TPA 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 intersect the proposed repository footprint in every realization. This is necessary to obtain statistically meaningful estimates 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 (as explained below) 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 summarized in U.S. Geologic Survey (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 recurrence rate for all faulting). 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 existing faults (e.g., Morris et al., 1996) which once recognized will be set-back-from by design.

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 et al., 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 5,909 yr (13,000 divided by 2.2) yielding a effective 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 (5,909 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 recurrence for the base case input file.

3.1.1 FAULTO Parameters

The input parameters for the FAULTO module are summarized in table 3-1. 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 the surface at YM are rarely less than 45°. Therefore, the problem essentially reduces to two-dimensions. 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 (see table 2-4 of Ghosh et al., 1997) are too small to significantly affect performance of the proposed repository given a 10,000 or even 20,000 yr period of concern.

18/94

Table 3-1. Parameter values for the faulting events module of iterative performance assessment 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 Probabilistic Seismic Hazard Analysis (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	Electric Power Research Institute (1993); Stirewalt et al. (1995); USGS (1996)

3.1.2 FAULTO Assumptions and Abstractions

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 release. In some cases, the opposite is true. The consequence may be underestimated mainly owing to lack of

knowledge of the exact mechanisms involved. 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 repository design. This assumption is conservative because most geological observations assume that 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 provide evidence for repeated earthquake ruptures (e.g., U.S. Geologic Survey, 1996).

- There is no link between faulting, seismicity, and volcanism in the TPA Version 3.1.1. 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 close to the repository. In both cases, the assumptions are nonconservative.

- The orientation of the emplacement drifts are not considered, yet, 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 Version 3.1.1 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.

- For simplicity, fault length, fault zone width, fault orientation, and displacement were sampled independent of each other (i.e., no specified correlations in the sampler). 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 wide (greater than 100 m) fault zones. In future versions of the code, correlations in sample parameters of fault characteristics should be considered, which will improve the realism of the performance assessment.

- 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.

19/94

- For WP failure from faulting, it was simply assumed that once a minimum threshold displacement was exceeded, the WPs would fail. WP failure in the faulting modules was not linked to a WP failure mechanism. This assumption is conservative.

- In both the stand-alone and TPA module versions, 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 co-seismic rupture on all existing faults in the repository region. 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, the number of WPs disrupted by the faulting event may be significantly more than that predicted by the FAULTO module. Therefore, this assumption is nonconservative.

3.2 PROCEDURES

3.2.1 Sensitivity Runs

Sensitivity analyses with different parameters of the FAULTO module in the TPA code were conducted to estimate the effects of variation of these parameters on the potential performance of the proposed repository. Different combinations of disruptive scenarios were examined (e.g., all three disruptive scenarios—faulting, seismic, and volcano—on or only faulting on) together with either localized or uniform corrosion and different recurrence intervals of faulting (table 3-2). Changes in corrosion were accomplished by changing the oxygen partial pressure value to a low value (2×10^{-5}) for cases with no localized corrosion and at the base case value for runs with localized corrosion. 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/yr), Total U.S. Environmental Protection Agency Release (normalized), and number of WPs 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 WPs failed owing to different disruptive events was 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 TPA Version 3.1.1 runs retained all parameters except those in the FAULTO module and the groundwater variables at their respective mean values. Only parameters belonging to the FAULTO required module were sampled from their respective population distributions. The threshold displacement

Table 3.2. FAULTO sensitivity runs

Run	Input File	Distance to Critical Group	Time Period (yr)	Recurrence Interval (yr)	Localized Corrosi	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	5,000	no	yes
FLTO_Run5	mean value	5	20,000	500	no	yes
FLTO_Run6	mean value	20	20,000	5,000	yes	yes
FLTO_Run7	mean value	20	20,000	200,000	yes	yes
FLTO_Run8	mean value	20	20,000	5,000	no	yes
FLTO_Run9	mean value	20	20,000	500	no	yes
FLTO_Run10	mean value	5	20,000	5,000	no	no
FLTO_Run11	mean value	20	20,000	5,000	no	no

level for WP 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 WPs 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 Version 3.1.1 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.

3.2.2 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 about the true mean (Scheaffer and McClave, 1982). For example, both x and y should be normally distributed. The error component of the model (i.e., 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 the probability distribution functions for the independent and dependent variables are not necessarily known. 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 3-1. For example, width of faults trending northwest has a beta distribution with $\alpha = 1.25$ and $\beta = 15$, a distribution highly skewed toward left, that is, toward 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 the same is done for y's. If a correlation is demonstrated to be present nonparametrically, then it is really there. Nonparametric correlation is more 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.

3.3 RESULTS AND DISCUSSION OF FAULTO SENSITIVITY ANALYSES

3.3.1 Sensitive Input Parameters

Results for the sensitivity runs are summarized in appendixes B–M. Results for each run are given in terms of Peak TEDE (rem/yr), EPA release, and number of WPs 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 or WPs disrupted is fault zone width. Otherwise, factors that control groundwater flow were the only 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.

3.3.2 Five and 20 Kilometers

Comparison of runs in which all parameters were held constant, except for the distanc the critical group, are shown in figure 3-1. Results are provided for cases in which the recurrence i rvals were varied between 500 and 50,000 yr. Results show approximately a 3.5 orders of magnitud change in dose between 5 and 20 km. Doses are of up to one rem/yr for the 5 km distance and 1.0×0^{-4} and 5×10^{-4} rem/yr for 20 km distance.

3.3.3 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 3-2. Backfill is not assumed to affect WP failure owing to faulting, only the associated hydrological and thermal calculations. Results show that whether the drifts are backfilled or not does not influence dose response.

3.3.4 Localized Corrosion and Uniform Corrosion

WP corrosion is a critical factor in whether or not faulting can affect WPs. Once the WPs 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 localized 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 3-3). These results confirm that faulting is only important to performance if WPs do not fail by localized corrosion is first.

3.3.5 Effect of Fault Length

The length of the northeast trending faults ranges from 1.2 to 50 km. Therefore, the number of WPs failed only weakly correlated with the length of faults only at the low values of fault length. The longest dimension in the present repository footprint is about 4 km. At higher values of fault length, the correlation between number of WPs 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 3-4a and 3-4b.

3.3.6 Effect of Fault Orientation

The northeast trending faults have strikes ranging from N5°W to N25°E. Figure 3-5 shows schematically the effects of fault orientation on number of WP disruptions. 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 3-5 shows that the area of the repository disrupted by fault movement does not vary significantly with the fault orientation. Therefore, fault orientation has negligible impact on number of WPs disrupted and, consequently, on the peak doses. This result depends on the earlier stated assumption that the orientation of the emplacement drifts is not specified (i.e., assumed random) in the current TPA (Version 3.1.1) model.

21/94

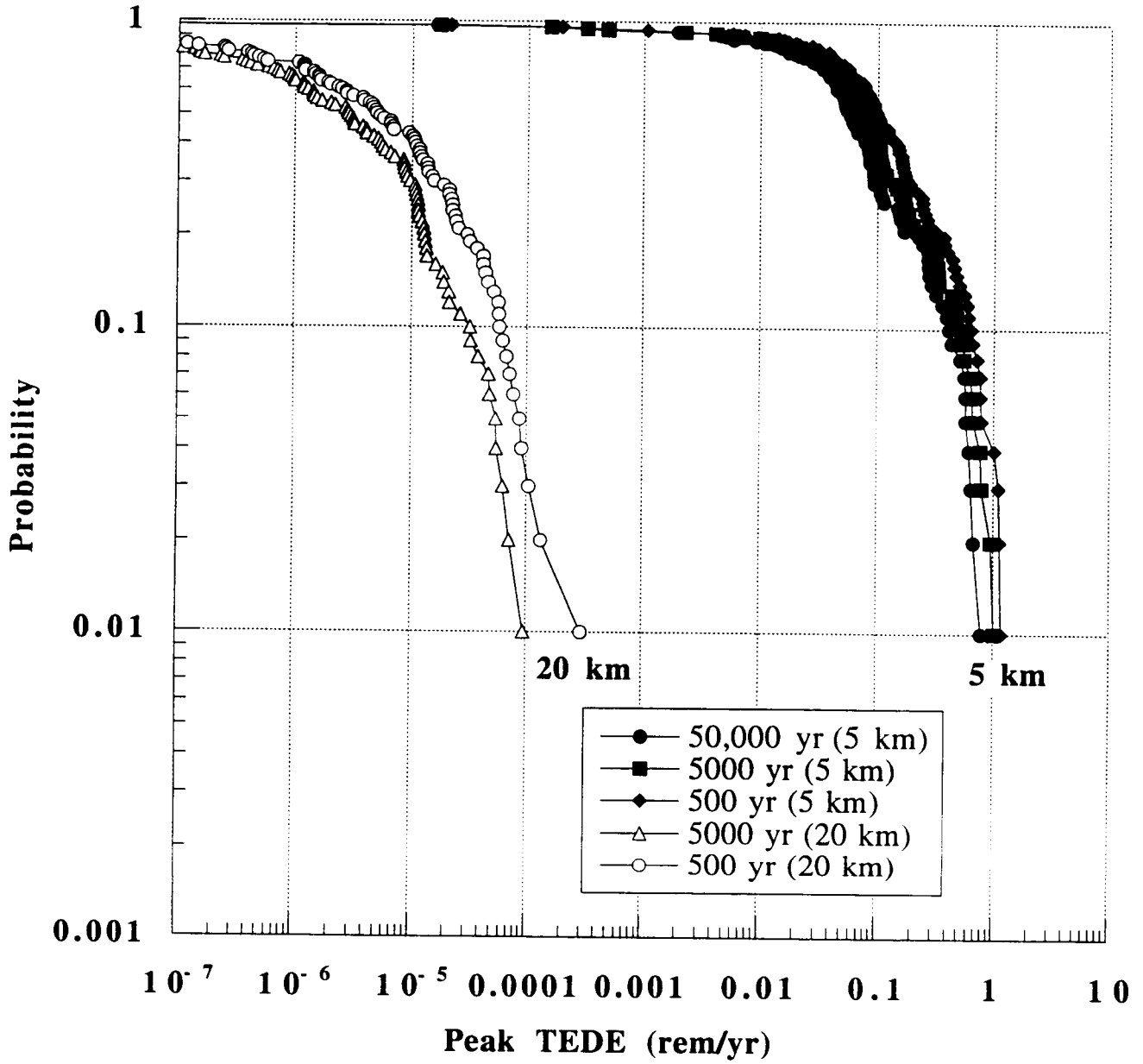


Figure 3-1. Probability plot of peak total effective dose equivalent (TEDE) comparing differences in recurrence intervals for critical group at 5 and 20 km

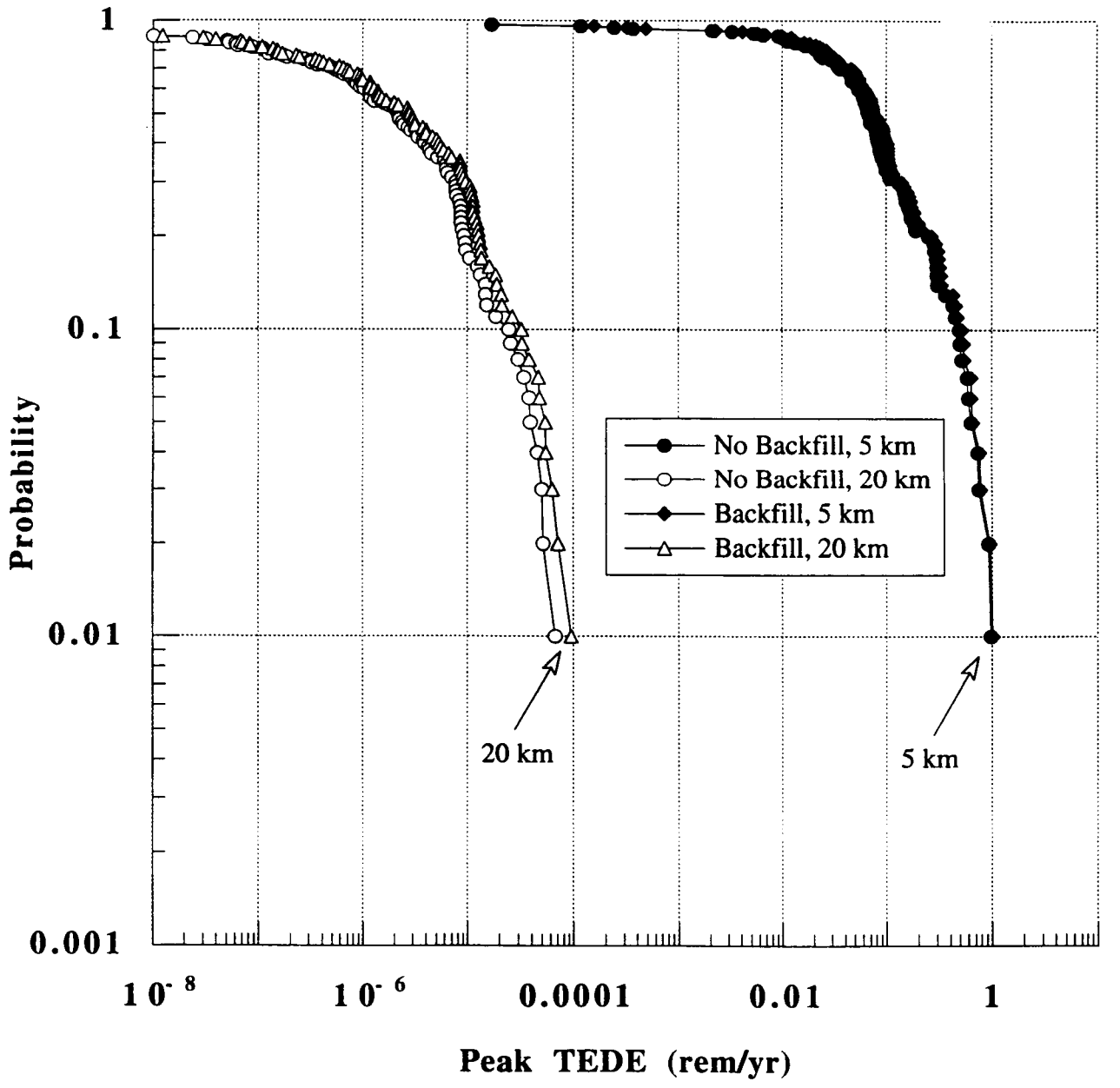


Figure 3-2. Probability plot showing differences in dose for backfilled and unbackfilled drifts for critical group at 5 and 20 km

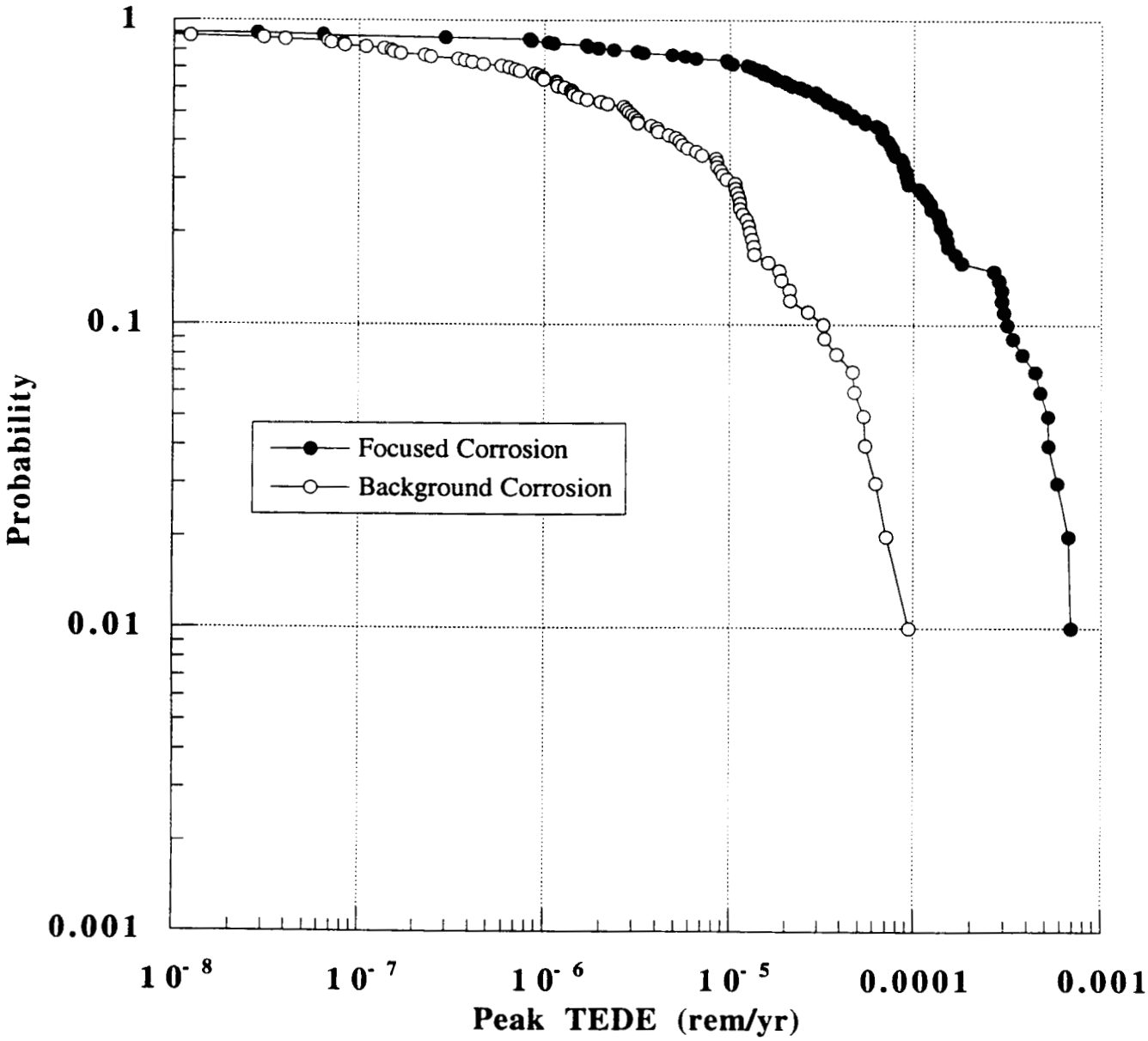


Figure 3-3. Probability plot showing difference in dose to a critical group at 5 km for localized and uniform corrosion

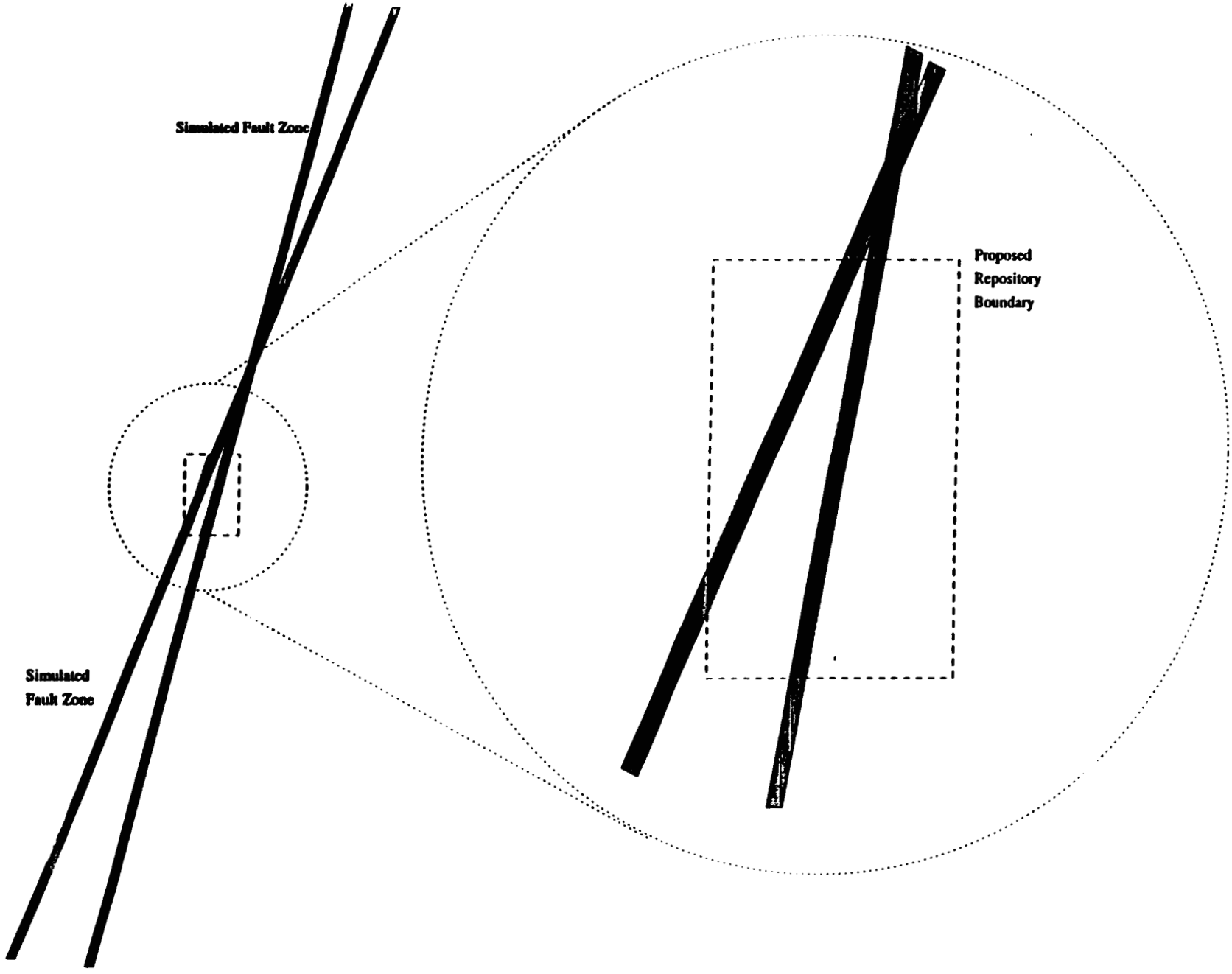


Figure 3-4a. Effect of fault zone length on waste package disruption: fault length significantly longer than proposed repository

23/94

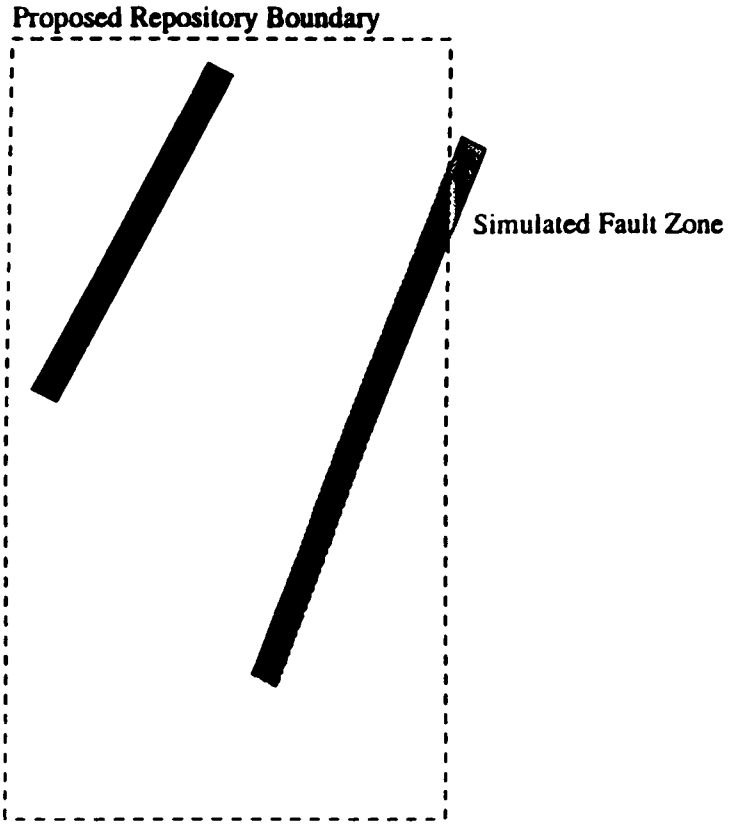
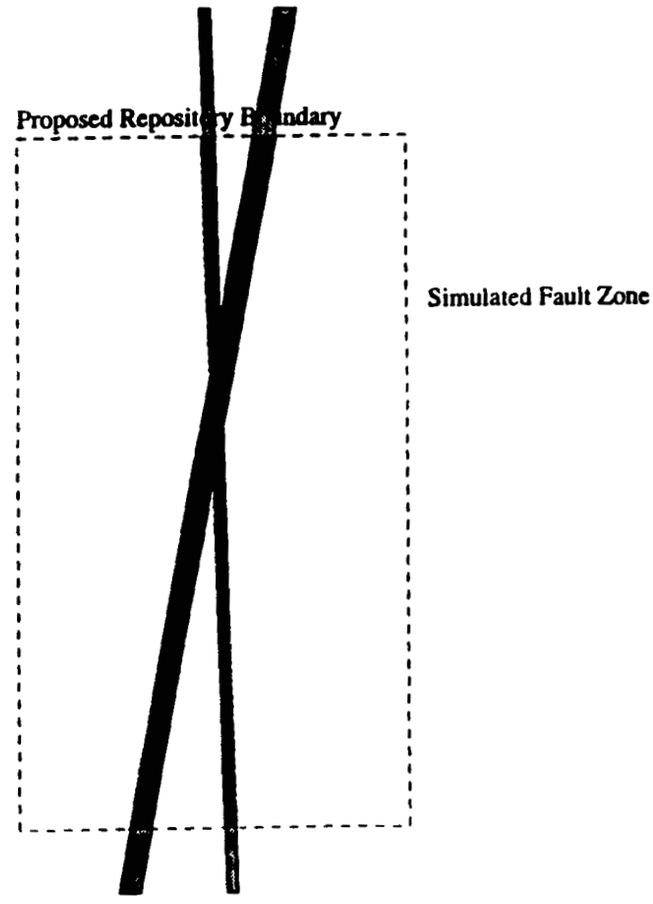


Figure 3-4b. Effect of fault zone length on waste package disruption: fault length comparable to proposed repository



Fault Orientation: N5W to N25E

Figure 3-5. Effect of fault orientation on waste package disruption

24/44

3.3.7 Effect of Fault Slip and Threshold Displacement

Magnitude of fault slip does not correlated with the number of WPs disrupted as the WPs failure criterion is based on fault displacement. In all runs of the TPA Version 3.1.1, the threshold displacement of WPs disruption was fixed at 0.05 m, the minimum amount of fault slip. Consequently, every generated fault had a finite number of WP disruptions and magnitude of fault slip was not the parameter influencing the outcome of the simulation run.

3.3.8 Cumulative Fault Displacement Rate

The cumulative fault displacement rate for the faults in the YMR is low and 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.

3.3.9 Fault Zone Width

The width of the simulated fault zone is directly related to the area of the proposed repository or emplacement area disrupted by the faulting event. As the WPs are assumed to be uniformly distributed over the entire emplacement area in the TPA code, the number of WPs disrupted is directly proportional to the width of the fault zone (illustrated schematically in figure 3-6).

3.3.10 Recurrence Interval

The recurrence interval essentially controls the time when faulting occurs. Recurrence interval has little effect on the number of WPs impacted and thus, on dose (figure 3-7) 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 critical group located at a given distance from the proposed repository will be higher.

3.4 RECOMMENDATIONS

3.4.1 Recommendations for Current TPA FAULTO Module

Assuming no enhanced localized corrosion of the WPs, fault zone width is the most sensitive parameter to peak dose in the FAULTO module. There is only a mild sensitivity to the timing of the faulting event (in these analyses controlled by the recurrence interval). If the WPs fail prior to faulting, then faulting is not a factor in the overall system performance. Dose values from faulting are not significant compared to the order of magnitude larger doses of the other processes like WP failure and seismicity.

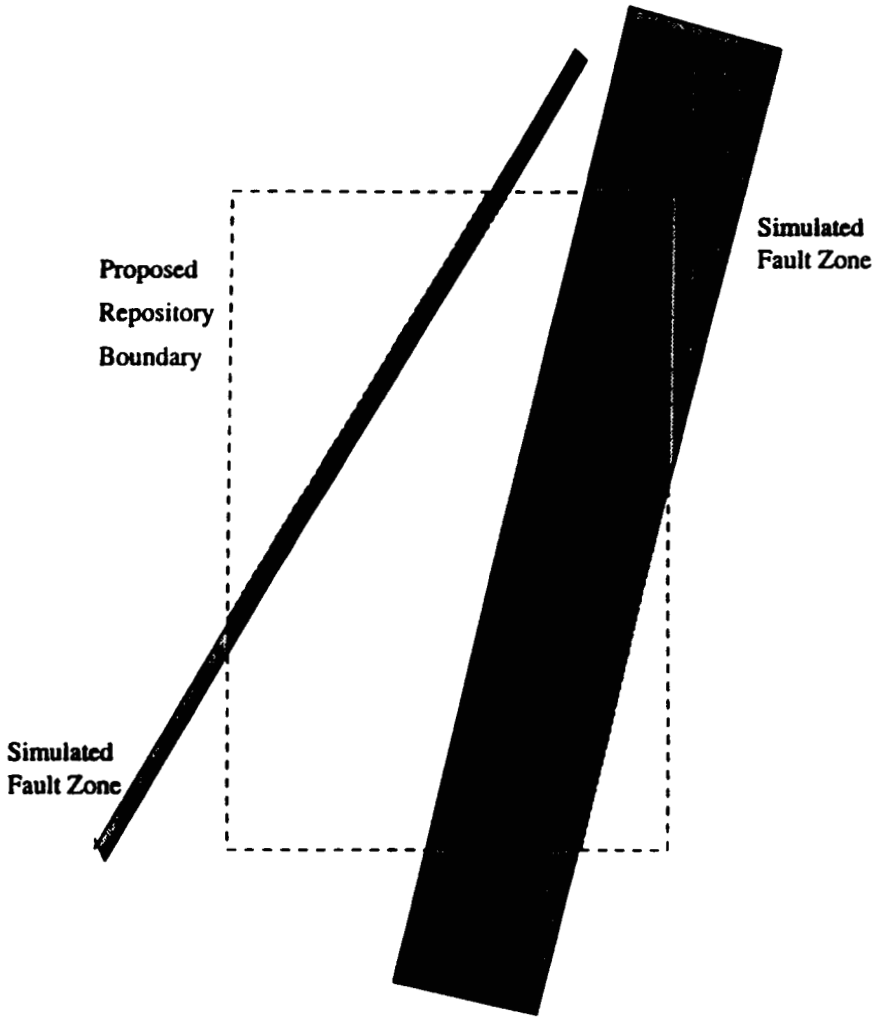


Figure 3-6. Effect of fault zone width on waste package disruption

25/94

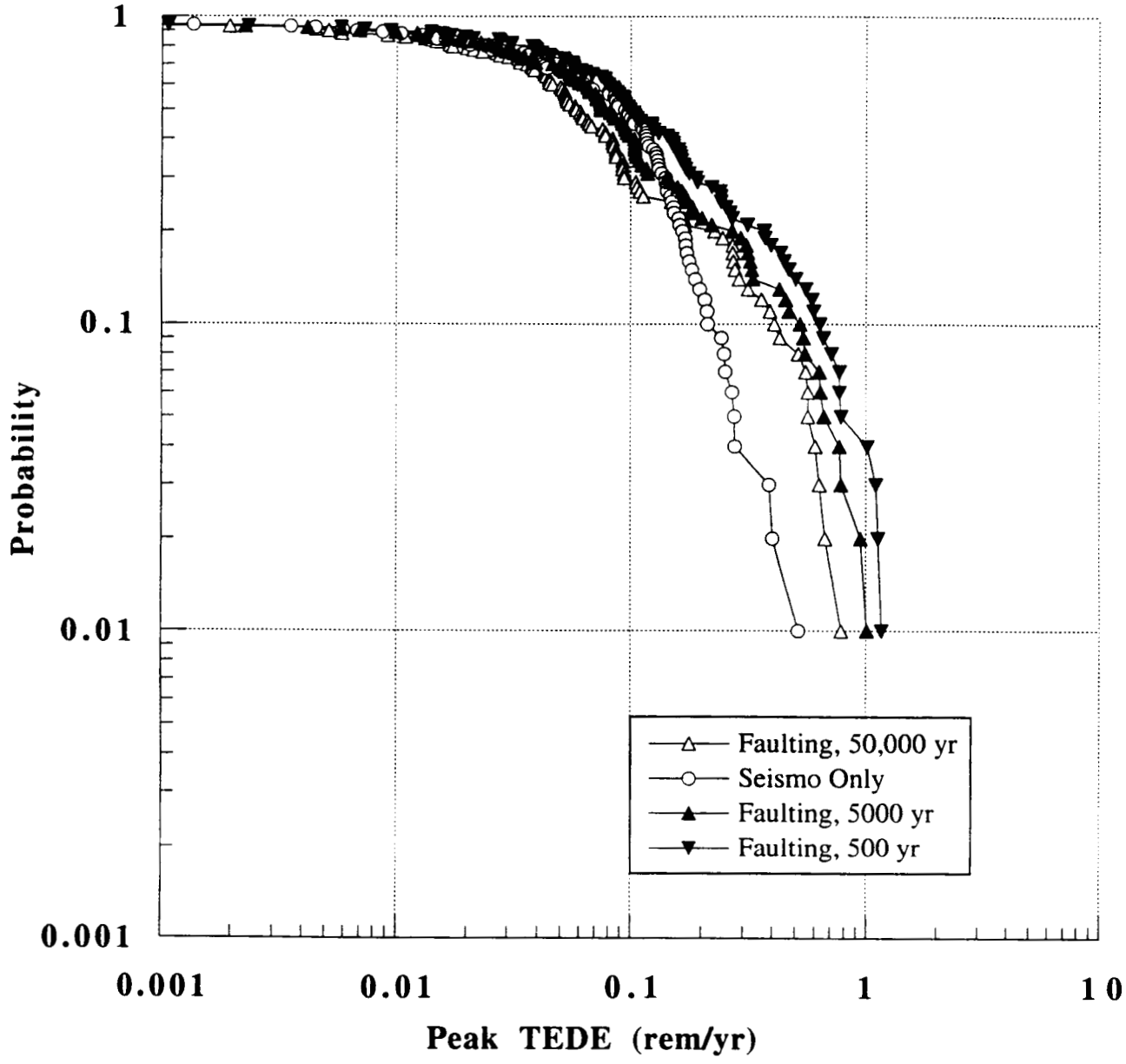


Figure 3-7. Probability plot showing dose to the critical group at 5 km for recurrence intervals between 500 and 50,000 yr

Given these results, the following changes are recommended to the input parameters in the FAULTO module for the TPA Version 3.1.1 production runs:

- Fix the recurrence rate at 200,000 yr.
- Use a threshold displacement value of 0.20 m consistent with the recommended mean value of fault offset given below.
- Use the mean values for fault orientation.
- Set the fault length to 8.0 m, twice the largest dimension of the repository footprint. The 2x value is needed because faults are generated from the midpoint and any fault smaller than 8.0 km initiated on the repository boundary may not transect the repository.
- Keep the fault zone width PDFs as before, pending ongoing SDS investigations.
- Set the fault displacement values at their means (0.5 m).
- Set the cumulative displacement values at 0.00005 m/yr. These are not significant to performance, but small values are required as placeholders for the variables in the code.

Details of the FAULTO input parameters are summarized in table 3-3.

3.4.2 Recommendations for Future Conceptual Model and Abstractions

As discussed in the previous sections, the current version of FAULTO is based on a very simplified conceptualization of faulting. For the most part, this conceptualization and associated abstractions are conservative, at least in the sense that the effects of faulting on repository performance are greater than anticipated if a more realistic model of faulting were implemented. For example, the current code assumes that half of the faulting in the next 10,000 to 20,000 yr will occur on faults not set back from in repository design (new, blind, or otherwise underappreciated faults). The consensus among geological literature (e.g., Morris et al., 1996) is that most faulting and perhaps all faulting in the next 10,000 to 20,000 yr will occur on existing faults, those that will be accounted for in repository design. A second example is that there is no correlation between fault characteristics sampled by the code (e.g., width, length, displacement), contrary to what is generally observed in nature. Larger faults typically have larger displacements. In the current version of the code, even small faults have the potential to affect a relatively large portion of the repository.

Future versions of the code could add realism to the total system performance assessment by adopting a different approach to the way in which faulting is modeled. Because faulting over the next 10,000 to 20,000 yr will likely occur on existing faults that will be set back from in repository design, the real question is whether secondary deformation associated with faulting will cause significant damage to the WPs. Secondary damage includes co-seismic ruptures on secondary faults and fracturing of bedrock in both the hangingwall and footwall of the master fault. In this conceptualization, each of the block-bounding faults, like the Bow Ridge or Solitario Canyon would be considered independently. Recurrence for each of these faults would be derived directly from the available paleoseismic and geological data (e.g., USGS, 1996). Probability distribution functions (PDFs) that describe the amount and style of

deformation in the hangingwall and footwall of these master faults could be derived from detailed mapping of the Exploratory Studies Facility or numerical models of normal faulting deformation (e.g., Stamatakos et al., 1997). The PDFs could be scaled so that larger displacement events on the block-bounding faults produces relatively greater co-seismic deformation in the hangingwall and footwall regions. The code could even be adapted to account for possible segmented faulting, in which several faults that are unconnected, at least at the surface, rupture simultaneously. Fault segmentation appears to be a common characteristic of normal faulting in the Basin and Range (e.g., Willemse, 1997). Moreover, this approach would allow the effects of faulting on fracture flow to be assessed within the faulting module.

Table 3-3. FAULTO input parameters for base case

Parameter Type	Input Parameter	Comment	Range	Reference
finiteexponential[1]	TimeOfNextFaultingEventinRegionOfInterest[yr]	Recurrence rate	100.0, 10000.0, 2.0×10^{-5}	Based on PSHA data, USGS (1996)
userdistribution	ThresholdDisplacementforFaultDisruptionOfWP[m]	Threshold fault displacement for disruption (m) Data input order: number of fault displacement values to be provided followed by equiprobable displacement values	4 0.1 0.2 0.3 0.4	CNWRA staff best estimate
uniform	XLocationOfFaultingEventInRegionOfInterest[m]	X location of faulting event in region of interest (m)	547400.0, 548600.0	Within repository
uniform	YLocationOfFaultingEventInRegionOfInterest[m]	Y location of faulting event in region of interest (m)	4076200.0, 4079040.0	Within repository
constant	ProbabilityForNWOrientationOfFaults	Probability for NW orientation of faults	0.05	Based on map of Scott and Bonk (1984)
uniform	RNtoDetermineFaultOrientation		0.0, 1.0	
constant	NWFaultStrikeOrientationMeasuredfromNorthClockwise[degrees]	NW strike orientation measured from N clockwise (degrees)	-32.5	Based on map of Scott and Bonk (1984)
constant	NEFaultStrikeOrientationMeasuredfromNorthClockwise[degrees]	NE strike orientation measured from N clockwise (degrees)	10	Based on map of Scott and Bonk (1984)
constant	NWFaultTraceLength[m]	NW fault trace length (m)	4,000	Based on map of Scott and Bonk (1984); Simonds et al. (1995)
constant	NEFaultTraceLength[m]	NE fault trace length (m)	4,000	Based on map of Scott and Bonk (1984); Simonds et al. (1995)
beta	[3]NWFaultZoneWidth[m]	NW fault zone width (m)	0.5, 275.0, 1.25, 15.0	Based on observational data from ESF, Ghosh et al. (1997); Stirewalt et al. (1995)
beta	[3]NEFaultZoneWidth[m]	NE fault zone width (m)	0.5, 365.0, 1.25, 15.0	Based on [illegible] data from ESF, Ghosh et al. [illegible]; Stirewalt et al. (1995)
constant	[4]NWAmountOfLargestCredibleDisplacement[m]	NW largest credible displacement (m)	0.5	USGS (1996)

Table 3-3. FAULTO input parameters for base case (cont'd)

Parameter Type	Input Parameter	Comment	Range	Reference
constant	[4]NEAmountOfLargestCredibleDisplacement[m]	NE largest credible displacement (m)	0.5	USGS (1996)
constant	NWCumulativeDisplacementRate[mm/yr]	NW cumulative displacement rate (m/yr)	0.00005	Assumed based on Electric Power Research Institute (1993)
constant	NECumulativeDisplacementRate[mm/yr]	NE cumulative displacement rate (m/yr)	0.00005	Assumed based on Electric Power Research Institute (1993)

Notes:

[1]See detailed discussion in section 3-1 of this report.

[2]No direct analyses of WP stability in fault zones exists. The 0.2 m value is the mean value of the original distribution and is consistent with the proposed fault zone displacement.

[3]Subject of ongoing SDS investigation.

[4]Median value of measured paleoseismic ruptures summarized in USGS (1996)

37/54

28/94

4 REFERENCES

Abrahamson, N.A., and W.J. Silva. 1997. Empirical response spectral attenuation relations for shallow crustal earthquakes. *Seismological Research Letters 68*: 94–127.

Brechtel, C.E., M. Lin, E. Martin, and D.S. Kessel. 1995. *Geotechnical Characterization of the North Ramp of the Exploratory Studies Facility, Volume I of II Data Summary*. SAND95–0488/1UC–814. Albuquerque, NM: Sandia National Laboratories.

Day, W.C., C.J. Potter, D.S. Sweetkind, R.P. Dickerson, and C.A. San Juan. 1997. *Bedrock geologic map of the central block area, Yucca Mountain*. U.S. Geological Survey Miscellaneous Investigations Series, Map 1-2601 Scale 1:6000. Denver, CO: U.S. Geological Survey.

Electric Power Research Institute. 1993. *Earthquake and Tectonics Expert Judgement Elicitation Project*. Geomatrix Project 3055-13. EPRI TR-102000. San Francisco, CA: Geomatrix Consultants, Inc.

Fedotov, S.A., and Ye.K. Markhinin. 1983. *The Great Tolbachik Fissure Eruption*. Cambridge, United Kingdom: Cambridge University Press.

Ferrill, D.A., G.L. Stirewalt, D.B. Henderson, J.A. Stamatakos, A.P. Morris, K.H. Spivey, and B.P. Wernicke. 1996. *Faulting in the Yucca Mountain Region: Critical Review and Analyses of Tectonic Data From the Central Basin and Range*. NUREG/CR-6401. Washington, DC: Nuclear Regulatory Commission.

Ghosh, A., R.D. Manteufel, and G.L. Stirewalt. 1997. *Faulting Version 1.0-A Code for Simulation of Direct Fault Disruption: Technical Description and User's Guide*. San Antonio, TX: Center for Nuclear Waste Regulatory Analyses.

Hoek, E., and E.T. Brown. 1982. *Underground Excavations in Rock*. London, England: Institution of Mining and Metallurgy.

Luhr, J.F., and T. Simkin. 1993. *Parícutin, The Volcano Born in a Mexican Cornfield*. Phoenix, AZ: Geoscience Press Inc.

Morris, A.P., D.A. Ferrill, and D.B. Henderson. 1996. Slip tendency analysis and fault reactivation. *Geology* 24: 275–278.

Popov, E.P. 1970. *Mechanics of Materials*. New York: Prentice Hall.

Press, W.H., B.P. Flannery, S.A. Teukolsky, and W.T. Vetterling. 1986. *Numerical Recipes: The Art of Scientific Computing*. Cambridge, United Kingdom: Cambridge University Press.

Sadigh, K., C.-Y. Chang, J.A. Egan, F. Makdisi, and R.R. Youngs. 1997. Attenuation relationships for shallow crustal earthquakes based on California strong motion data. *Seismological Research Letters 68*: 180–189.

Scheaffer, R.L., and J.T. McClave. 1982. *Statistics for Engineers*. Boston, MA: Duxbury Press.

Scott, R.B., and J. Bonk. 1984. *Preliminary geologic map of Yucca Mountain, Nye County, Nevada, with Geologic Sections*. USGS Open-File Report 84–494, Scale 1:12000. Denver, CO: U.S. Geological Survey.

Simonds, W.F., J.W. Whitney, K. Fox, A. Ramelli, J.C. Yount, M.D. Carr, C.D. Menges, R. Dickerson, and R.B. Scott. 1995. *Map of Fault Activity of the Yucca Mountain Area, Nye County, Nevada*. U.S. Geological Survey Miscellaneous Investigations Series Map, 1-2520, Scale 1:24,000. Denver, CO: U.S. Geological Survey.

Stamatakos, J.A., P.S. Justus, D.A. Ferrill, R. Chen, and G.F. Ofoegbu. 1997. *NRC High-level Radioactive Waste Program Annual Progress Report: Fiscal Year 1996*. Chapter 3—Structural Deformation and Seismicity. NUREG/CR-6513, No. 1. Washington, DC: Nuclear Regulatory Commission.

Stirewalt, G.L., S.M. McDuffie, and R.D. Manteufel. 1996. A consequence analysis module to simulate fault displacement in the repository block at Yucca Mountain. *Methods of Seismic Hazards Evaluation: Focus '95*. La Grange Park, IL: American Nuclear Society: 169–177.

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

Timoshenko, S.P., and J.N. Goodier. 1987. *Theory of Elasticity*. New York: McGraw-Hall.

U.S. Department of Energy. 1995. *Topical Report—Seismic Design Methodology for a Geologic Repository at Yucca Mountain*. Yucca Mountain Site Characterization Project. Las Vegas, NV: Office of Civilian Radioactive Waste Management.

U.S. Geological Survey. 1996. *Seismotectonic Framework and Characterization of Faulting at Yucca Mountain, Nevada*. J.W. Whitney, Report Coordinator. Denver, CO: U.S. Geological Survey.

Weldy, J.R., S. Mohanty, J.A. Stamatakos, S.A. Stothoff, R.T. Pabalan, D.R. Turner, G.W. Wittmeyer, S.M. Hsiung, P.A. LaPlante, G.A. Cragnolino, L.H. McKague, B.E. Hill, and C.B. Connor. 1997. *Comparison of Reference Input Parameter Values for the Total System Performance Assessment of the Proposed Yucca Mountain Repository*. San Antonio, TX: Center for Nuclear Waste Regulatory Analyses.

Willemse, E.J.M. 1997. Segmented normal faults: Correspondence between three-dimensional mechanical models and field data. *Journal of Geophysical Research* 102: 675–692.

Wong, I.G., S.K. Pezzopane, C.M. Menges, R.K. Green, and R.C. Quittmeyer. 1995. Probabilistic seismic hazard analysis of the Exploratory Studies Facility at Yucca Mountain, Nevada. *Methods of Seismic Hazard Evaluation: Focus '95*, La Grange Park, IL: American Nuclear Society: 51–63.

29/94

APPENDIX A

SUMMARY OF RESULTS OF SENSITIVITY ANALYSES USING FAULTO MODULE

Table A-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	-0.2462	NA	-0.1037	-0.0024	0.3695/0.3559	-0.0289
	EPASUM	-0.2918	NA	-0.0921	-0.0228	0.2175/0.2079	-0.0595
	No. of WP	-0.0394	NA	-0.0822	-0.0470	0.9142/0.9134	0.0523
FLTO_Run2	Peak TEDE	-0.1904	NA	-0.1406	0.1392	0.5060/0.3341	-0.0317
	EPASUM	-0.2863	NA	-0.1673	0.1692	0.3527/0.2359	0.0556
	No. of WP	-0.0508	NA	-0.0523	0.0479	0.8904/0.8718	-0.0860
FLTO_Run3	Peak TEDE	NA	NA	NA	NA	NA	NA
	EPASUM	NA	NA	NA	NA	NA	NA
	No. of WP	NA	NA	NA	NA	NA	NA
FLTO_Run4	Peak TEDE	-0.1415	NA	-0.1302	0.1306	0.5369/0.4119	-0.0297
	EPASUM	-0.2043	NA	-0.1418	0.1443	0.4685/0.2889	-0.0070
	No. of WP	-0.0394	NA	-0.0822	0.0470	0.8904/0.8718	-0.0860
FLTO_Run5	Peak TEDE	-0.0894	NA	-0.0953	0.1100	0.5532/0.4495	-0.0523
	EPASUM	-0.0779	NA	-0.1144	0.1250	0.5298/0.3697	-0.0561
	No. of WP	-0.0352	NA	-0.0822	0.0470	0.8904/0.8718	-0.0859
FLTO_Run6	Peak TEDE	0.1423	NA	-0.0098	-0.0017	-0.0385/0.0548	-0.0810
	EPASUM	0.1142	NA	-0.0020	-0.0301	-0.0001/0.0621	-0.0831
	No. of WP	-0.3005	NA	-0.2027	0.0355	0.4581/0.5434	0.0756
FLTO_Run7	Peak TEDE	0.0638	NA	-0.0088	-0.0091	-0.0562/0.0445	-0.0790
	EPASUM	0.0372	NA	-0.0002	-0.0300	-0.0088/0.0573	-0.0817
	No. of WP	-0.3354	NA	-0.1354	0.0253	0.4373/0.4615	-0.0715
FLTO_Run8	Peak TEDE	-0.1989	NA	-0.0119	0.1656	0.2983/0.1733	-0.0716
	EPASUM	-0.2201	NA	-0.1196	-0.0165	0.3548/0.1968	-0.0682
	No. of WP	0.0020	NA	-0.2045	-0.0030	0.9332/0.9494	0.0928
FLTO_Run9	Peak TEDE	-0.0984	NA	-0.1344	0.0386	0.5078/0.2634	-0.0025
	EPASUM	-0.0905	NA	-0.1258	-0.0663	0.4751/0.3167	-0.0295
	No. of WP	0.0090	NA	-0.2045	-0.0030	0.9332/0.9494	0.0928
FLTO_Run10	Peak TEDE	-0.1302	NA	-0.1299	0.1348	0.5345/0.4201	-0.0331
	EPASUM	-0.1976	NA	-0.1333	0.1348	0.4815/0.2955	-0.0132
	No. of WP	-0.0394	NA	-0.0822	0.0470	0.8904/0.8718	-0.0859
FLTO_Run11	Peak TEDE	-0.2102	NA	-0.0228	0.1509	0.3198/0.1871	-0.0689
	EPASUM	-0.2316	NA	-0.1228	-0.0268	0.3782/0.2137	-0.0648
	No. of WP	0.0020	NA	-0.2045	-0.0030	0.9332/0.9494	0.0928

30/54

Table A-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	0.3143	0.1505	-0.0385	0.1971/0.2022	0.1390/0.2338	0.3826/0.5296
	EPASUM	0.3327	0.0874	-0.0478	0.1965/0.3163	0.1777/0.3081	0.3755/0.4955
	No. of WP	-0.0090	0.0265	-0.0190	0.0220-0.0068	-0.0425/-0.0368	-0.0044/0.0029
FLTO_Run2	Peak TEDE	0.3982	0.1496	-0.0739	0.1563/0.1616	0.2583/0.1956	0.4202/0.6418
	EPASUM	0.3468	0.0916	-0.0856	0.1815/0.2810	0.2867/0.2573	0.3422/0.5850
	No. of WP	0.0987	0.0524	-0.0565	-0.0251/0.0618	0.0228/0.0269	0.0571/0.0093
FLTO_Run3	Peak TEDE	0.4957	0.2074	-0.2043	0.1684/0.1406	0.3122/0.2238	0.6072/0.7406
	EPASUM	0.5575	0.0172	-0.0979	0.2200/0.3260	0.3714/0.2841	0.52540.6153
	No. of WP	NA	NA	NA	NA	NA	NA
FLTO_Run4	Peak TEDE	0.4172	0.1238	-0.0758	0.1165/0.1224	0.2841/0.1876	0.4453/0.6362
	EPASUM	0.4251	0.0616	-0.0521	0.1568/0.2815	0.2914/0.2503	0.4079/0.5737
	No. of WP	0.0987	0.0524	-0.0565	-0.0251/0.0618	0.0228/0.0269	0.0571/0.0093
FLTO_Run5	Peak TEDE	0.4363	0.1102	-0.0772	0.1217/0.0902	0.2474/0.1483	0.4763/0.6409
	EPASUM	0.4657	0.0194	-0.0293	0.1350/0.2777	0.2615/0.2328	0.4520/0.5618
	No. of WP	0.0987	0.0524	0.0565	-0.0251/0.0618	0.0228/0.0269	0.0571/0.0093
FLTO_Run6	Peak TEDE	0.4381	-0.0810	-0.0579	0.3173/0.5053	0.2869/0.3864	0.3611/0.3693
	EPASUM	0.4978	-0.0586	-0.0975	0.2697/0.4733	0.3035/0.3853	0.4394/0.3802
	No. of WP	-0.0303	-0.0963	0.1078	0.1520/0.0682	0.0307/0.0772	-0.1011/0.0182
FLTO_Run7	Peak TEDE	0.4335	-0.0798	-0.0611	0.3231/0.5033	0.2872/0.3908	0.3558/0.3691
	EPASUM	0.4957	-0.0583	-0.0970	0.2737/0.4767	0.3039/0.3853	0.4370/0.3776
	No. of WP	0.0518	0.0712	-0.0064	-0.0617/0.0121	0.0202/-0.0079	0.0620/0.0517
FLTO_Run8	Peak TEDE	0.3659	-0.0731	0.0209	0.0935/0.4449	0.1480/0.3666	0.3230/0.3710
	EPASUM	0.4296	-0.0921	-0.0426	0.0721/0.4348	0.1465/0.3495	0.3915/0.3657
	No. of WP	0.0893	-0.0351	0.0318	-0.1076/-0.0103	-0.0174/0.0367	0.0581/0.0176
FLTO_Run9	Peak TEDE	0.3293	-0.1087	0.0416	0.0547/0.4323	0.1137/0.3643	0.2891/0.3643
	EPASUM	0.4121	-0.1238	-0.0366	0.0708/0.4034	0.1870/0.3655	0.3666/0.3637
	No. of WP	0.0893	-0.0351	0.0318	-0.1076/-0.0103	-0.0174/0.0367	0.0581/0.0176
FLTO_Run10	Peak TEDE	0.4159	0.1192	-0.0697	0.0127/0.0249	0.0223/0.0467	-0.1223/0.1379
	EPASUM	0.4369	0.0596	-0.0455	0.0177/-0.0125	0.0106/0.0415	0.1510/0.2890
	No. of WP	0.0987	0.0524	0.0565	0.0007/0.0861	0.0077/0.0018	-0.0251/0.0618
FLTO_Run11	Peak TEDE	0.3659	-0.0757	0.0171	0.0872/0.4427	0.1496/0.3640	0.3248/0.3687
	EPASUM	0.4265	-0.0927	-0.0424	0.0625/0.4279	0.1450/0.3499	[illegible]
	No. of WP	0.0893	-0.0351	0.0318	-0.1076/-0.0103	-0.0174/0.0367	[illegible]

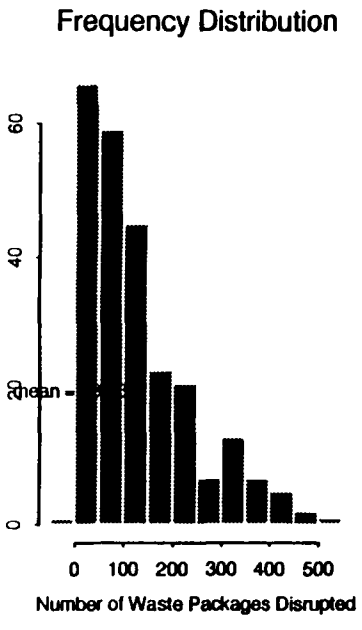
31/94

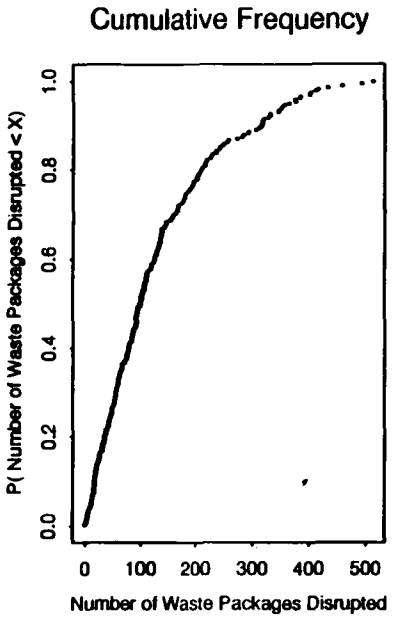
APPENDIX B

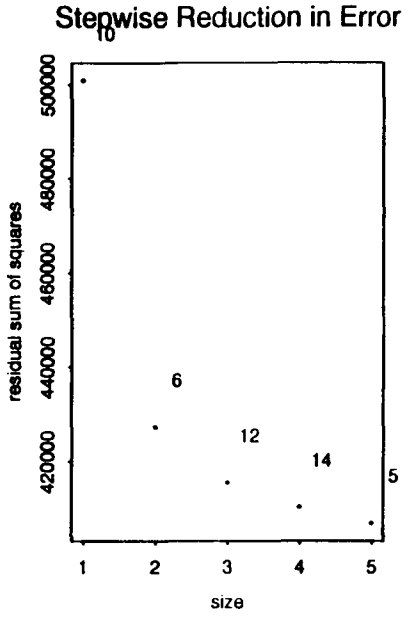
Run: FLTO_Run1

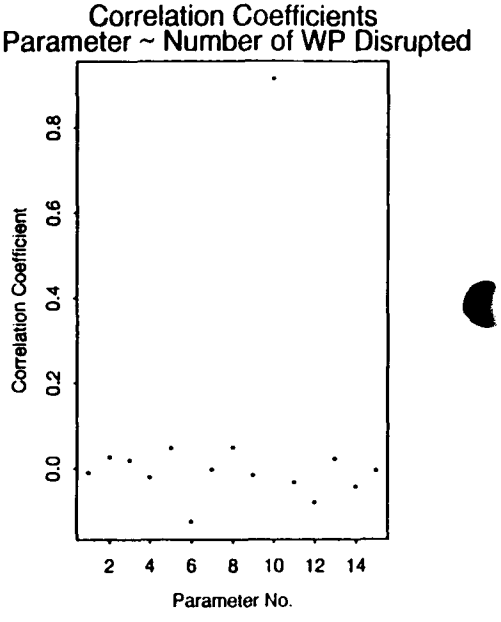
Distance to Critical Group = 5 km
Recurrence Interval = 200,000 yr
Only FAULTO, Uniform Corrosion, Backfill

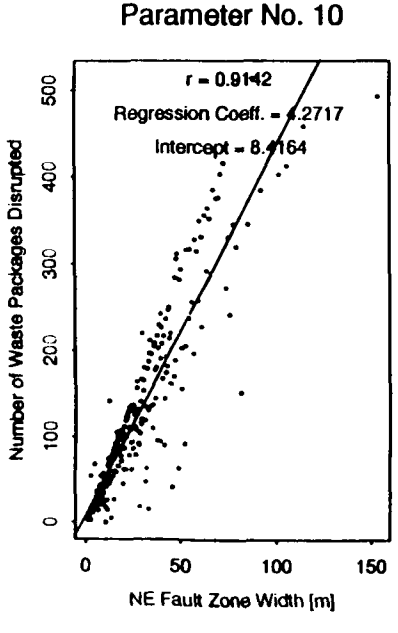
5 km Scenario
Summary Plots for Number of Waste Packages Disrupted

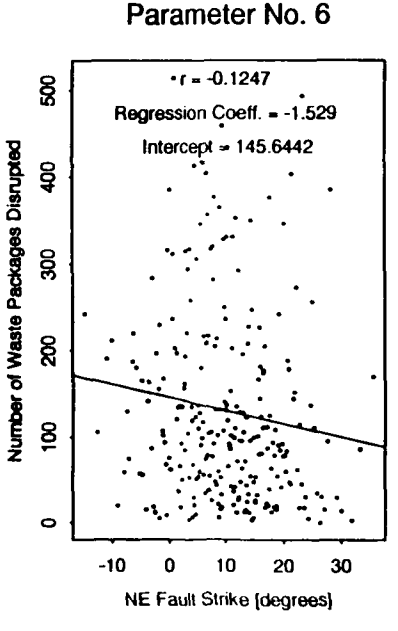


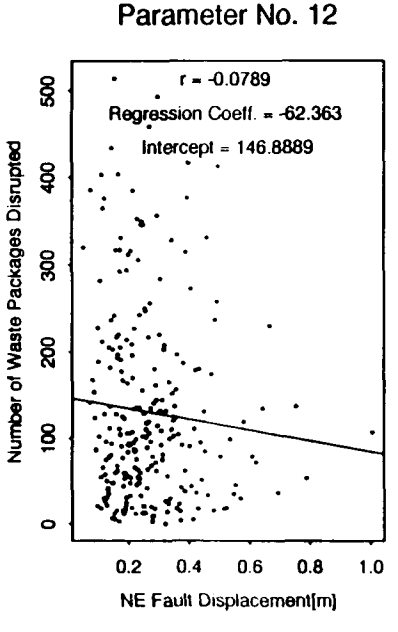


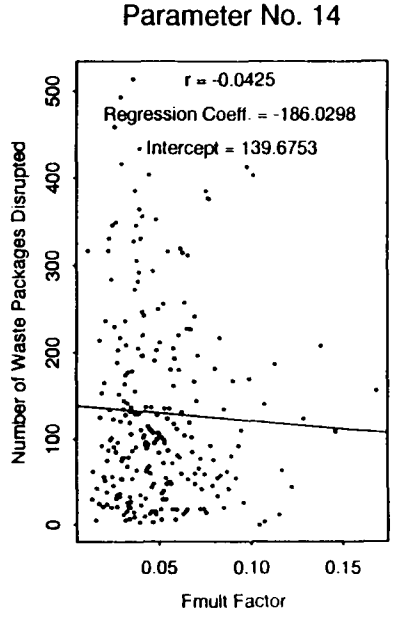






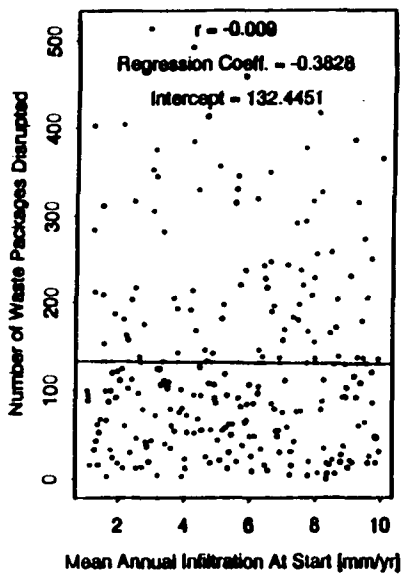




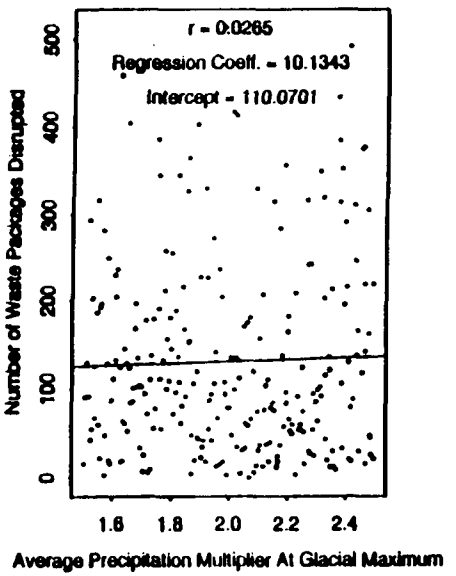


32/44

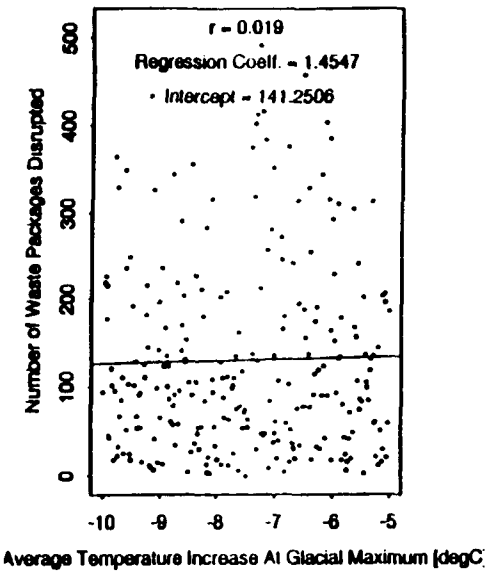
Parameter No. 1



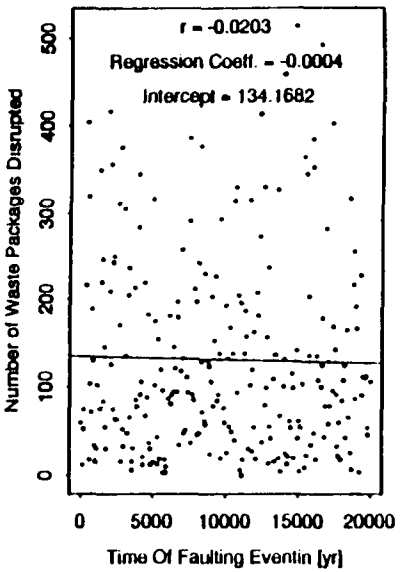
Parameter No. 2



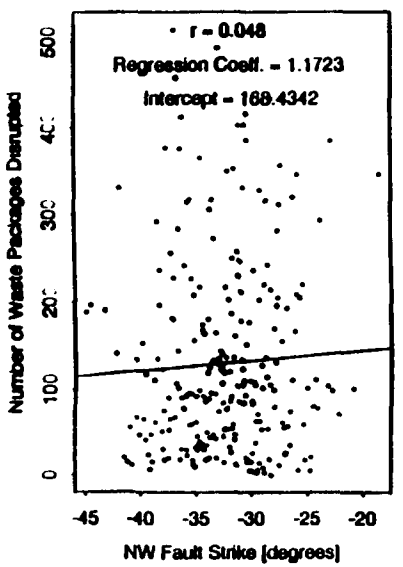
Parameter No. 3



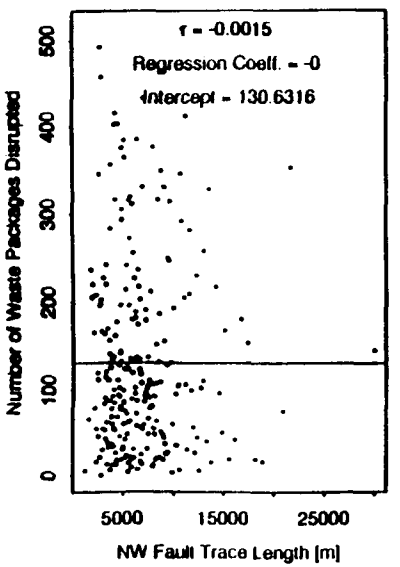
Parameter No. 4



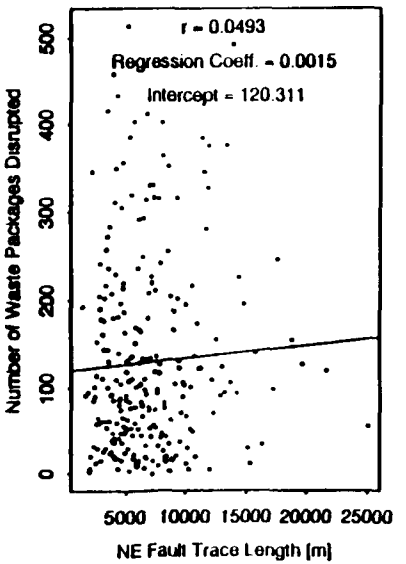
Parameter No. 5



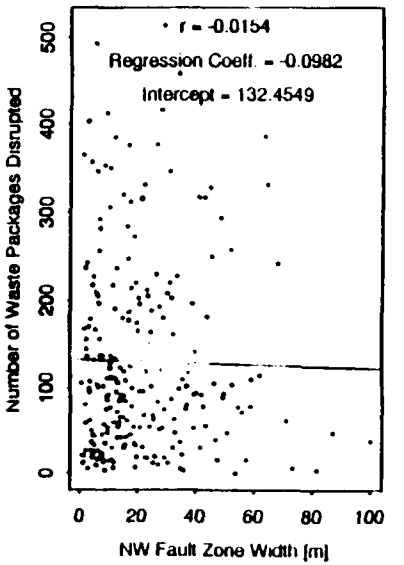
Parameter No. 7



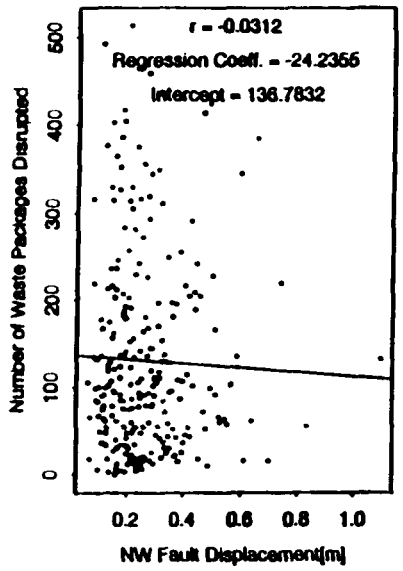
Parameter No. 8



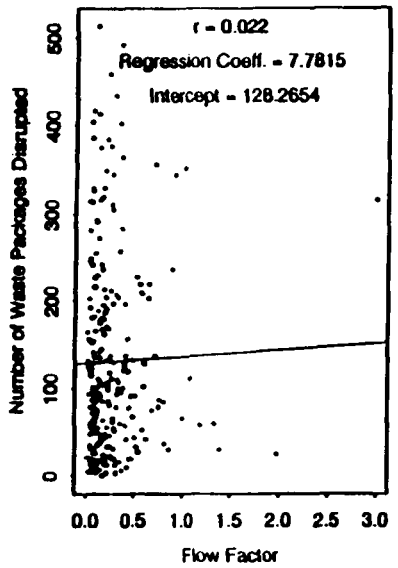
Parameter No. 9



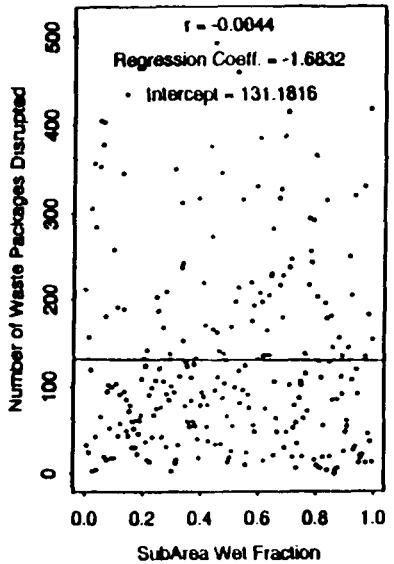
Parameter No. 11



Parameter No. 13

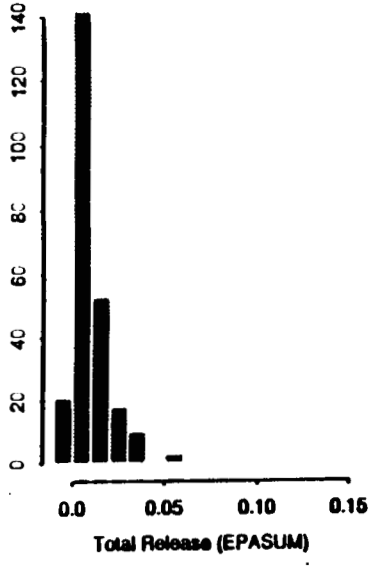


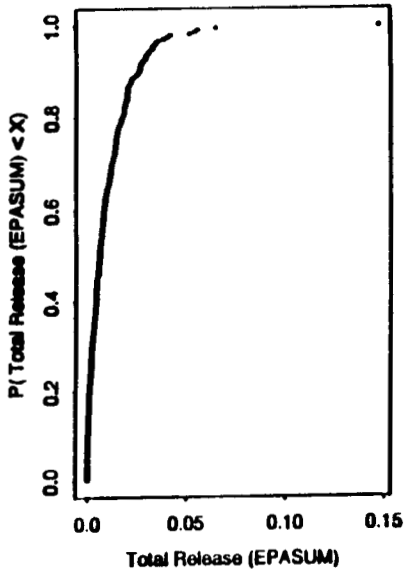
Parameter No. 15

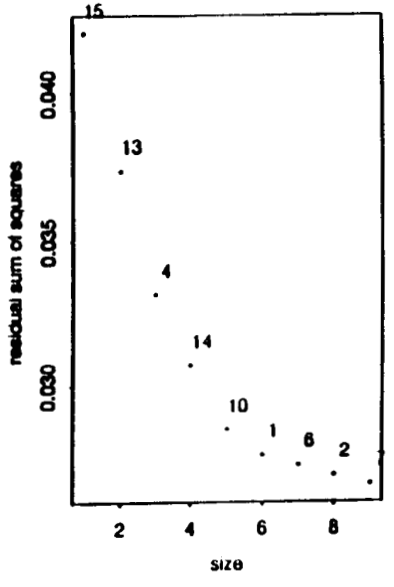


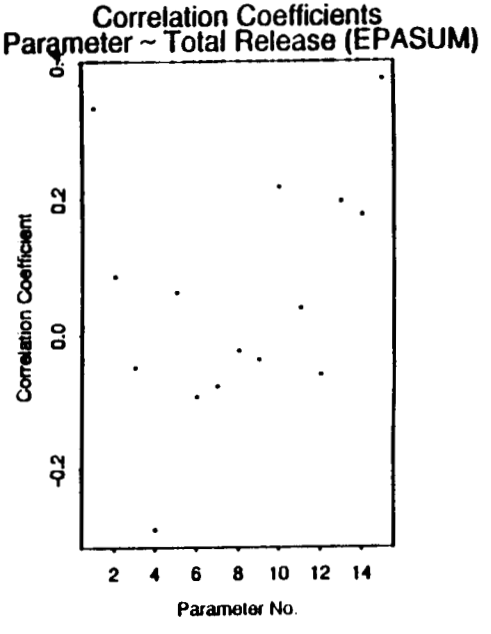
33/54

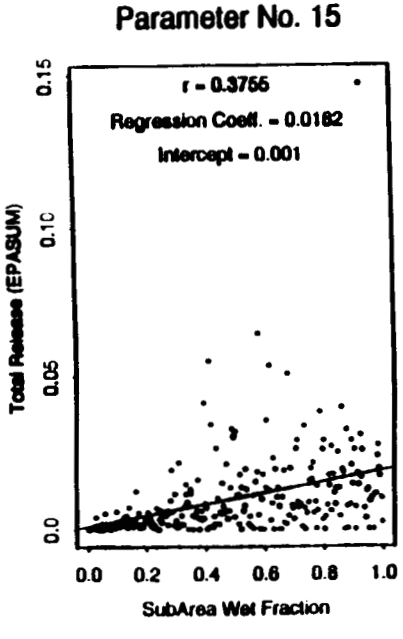
5 km Scenario
Summary Plots for Total Release (EPASUM)

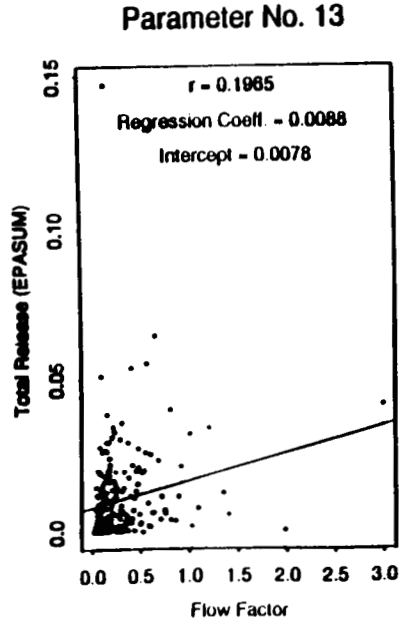


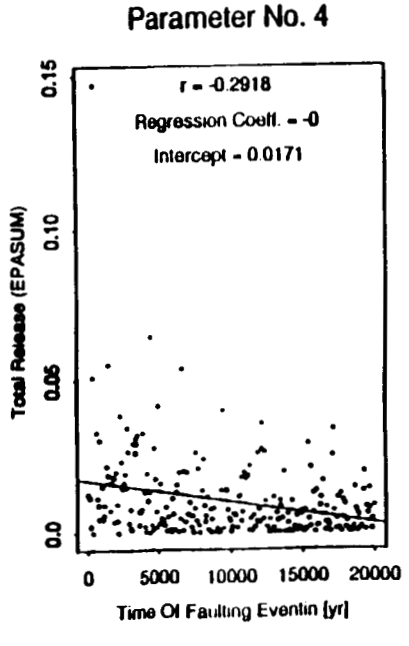


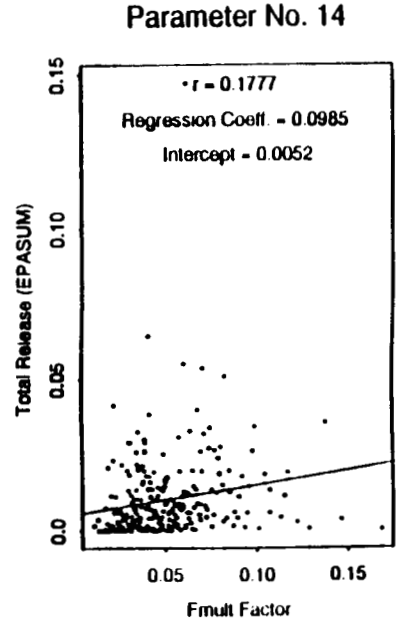


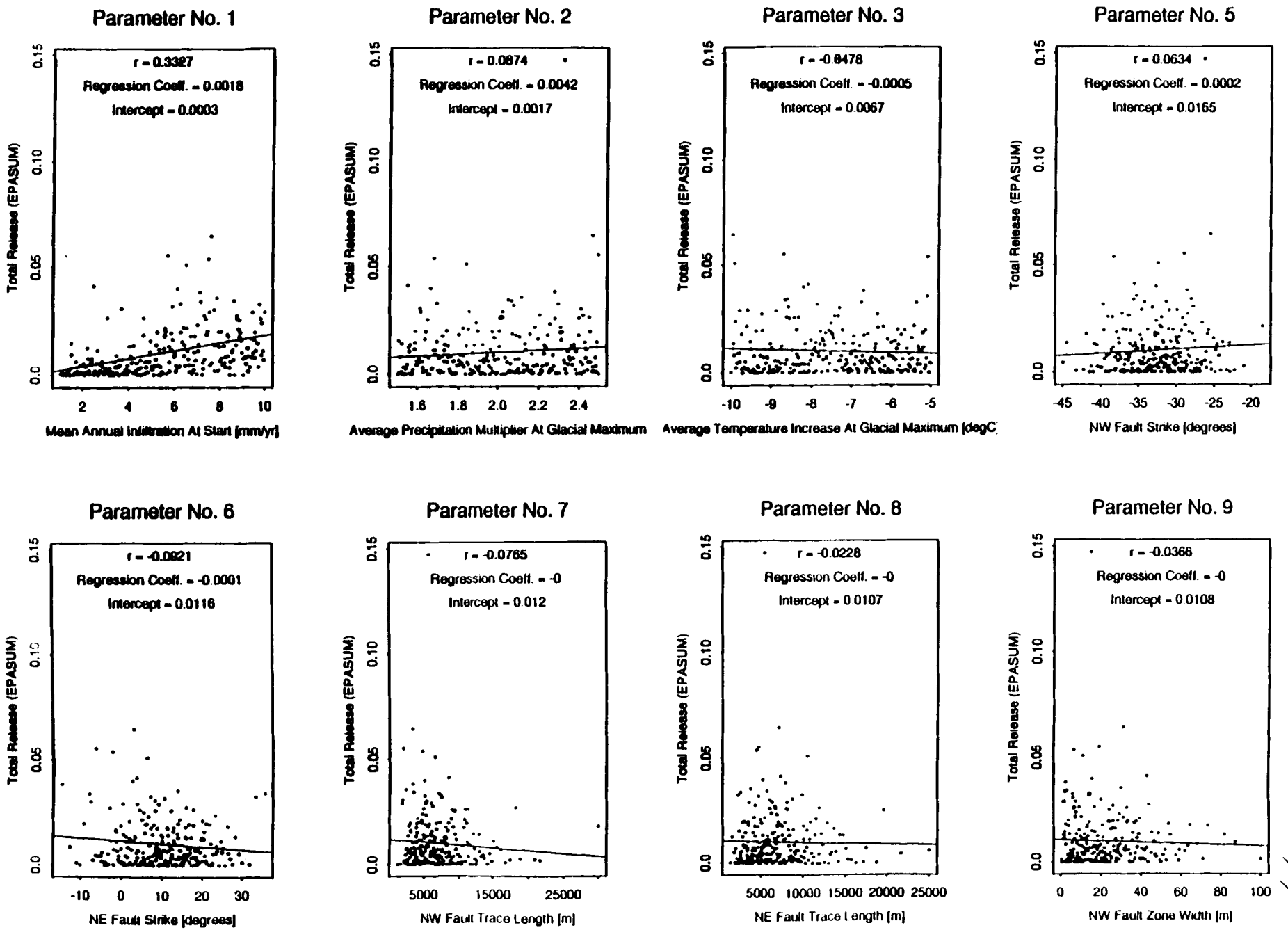




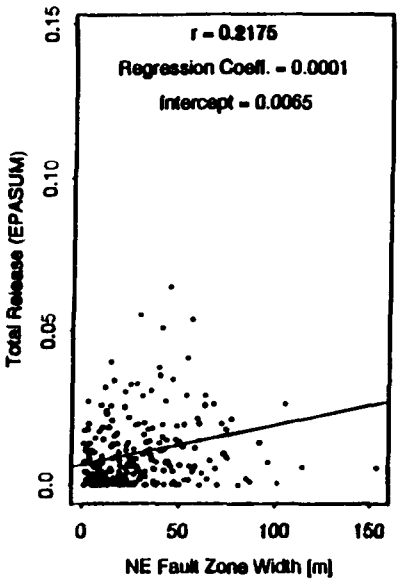




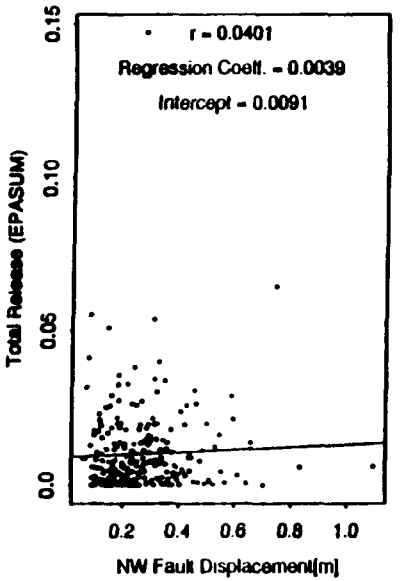



Parameter No. 1
r = 0.3327
Regression Coeff. = 0.0018
Intercept = 0.0003
Total Release (EPASUM)
Mean Annual Infiltration At Start [mm/yr]
Parameter No. 2
r = 0.0874
Regression Coeff. = 0.0042
Intercept = 0.0017
Average Precipitation Multiplier At Glacial Maximum
Parameter No. 3
r = -0.8478
Regression Coeff. = -0.0005
Intercept = 0.0067
Average Temperature Increase At Glacial Maximum [degC]
Parameter No. 5
r = 0.0634
Regression Coeff. = 0.0002
Intercept = 0.0165
NW Fault Strike [degrees]
Parameter No. 6
r = -0.0921
Regression Coeff. = -0.0001
Intercept = 0.0116
NE Fault Strike [degrees]
Parameter No. 7
r = -0.0765
Regression Coeff. = -0
Intercept = 0.012
NW Fault Trace Length [m]
Parameter No. 8
r = -0.0228
Regression Coeff. = -0
Intercept = 0.0107
NE Fault Trace Length [m]
Parameter No. 9
r = -0.0366
Regression Coeff. = -0
Intercept = 0.0108
NW Fault Zone Width [m]

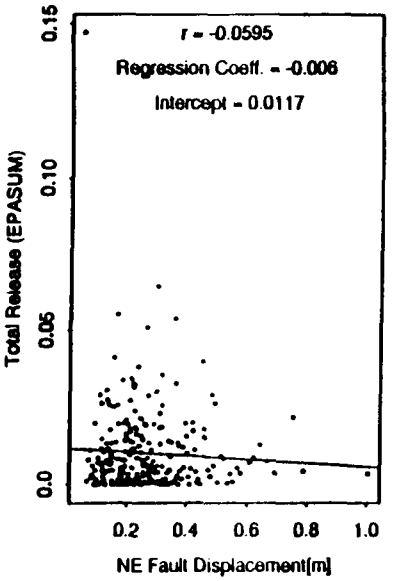
Parameter No. 10



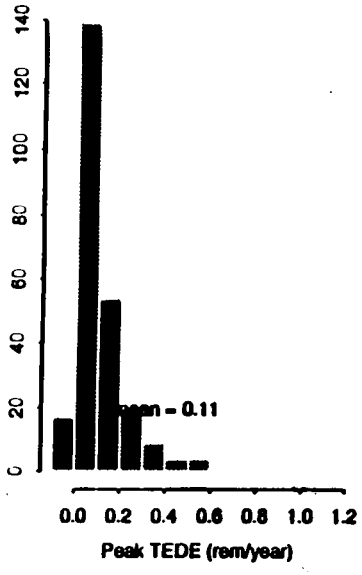
Parameter No. 11

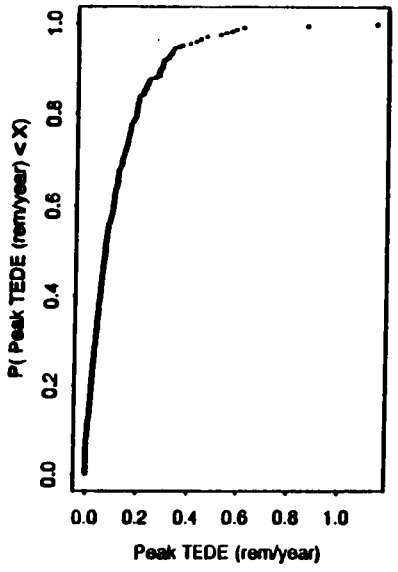


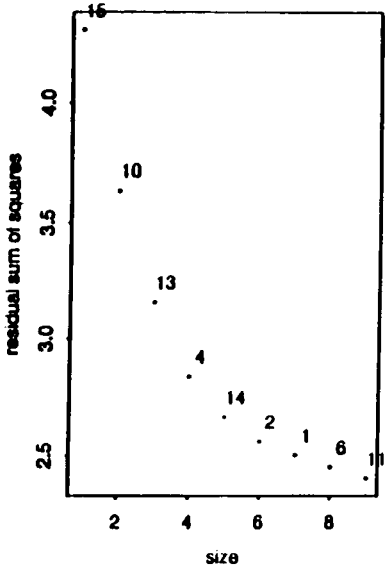
Parameter No. 12

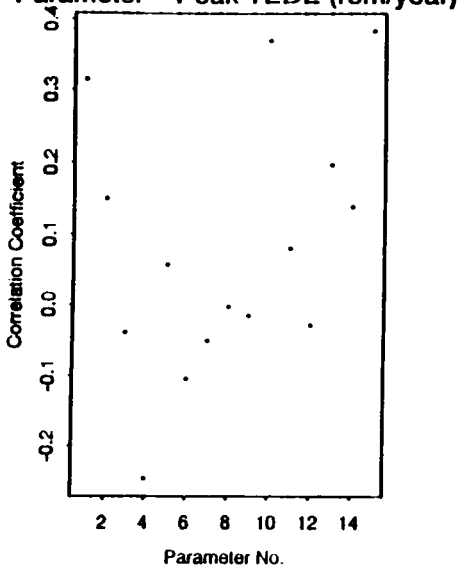


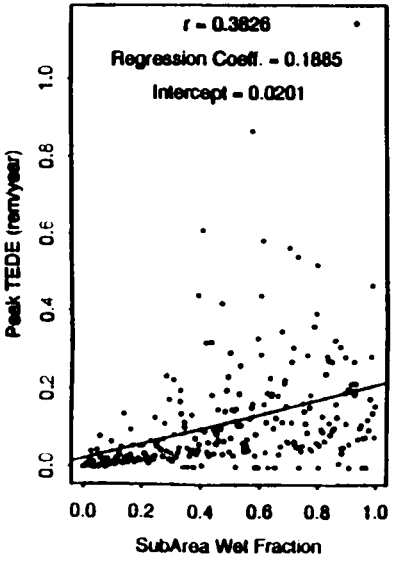
5 km Scenario
Summary Plots for Peak TEDE (rem/year)

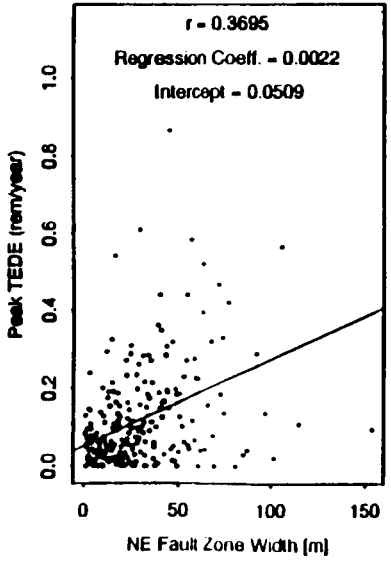


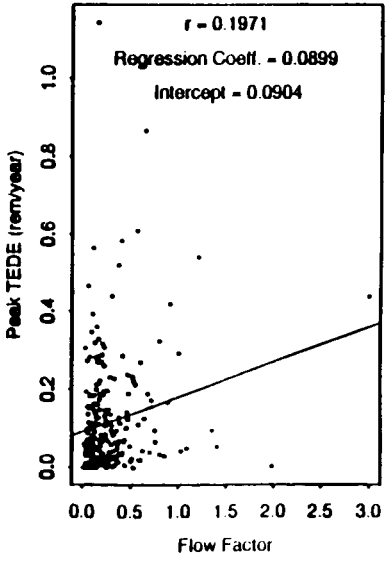


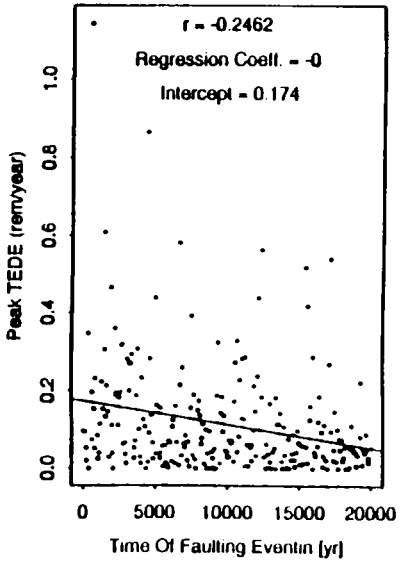




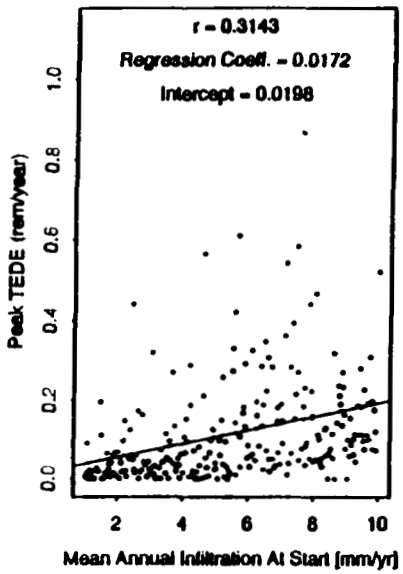




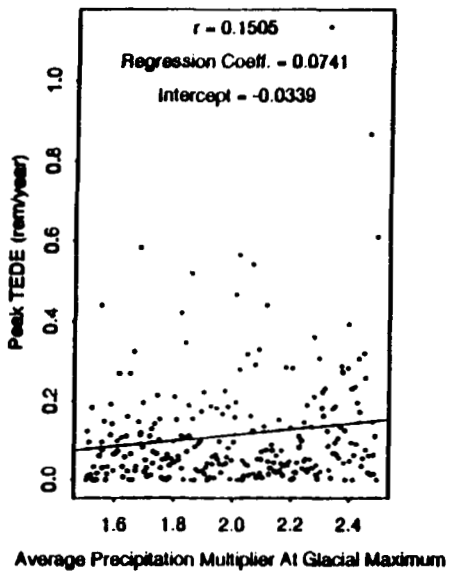




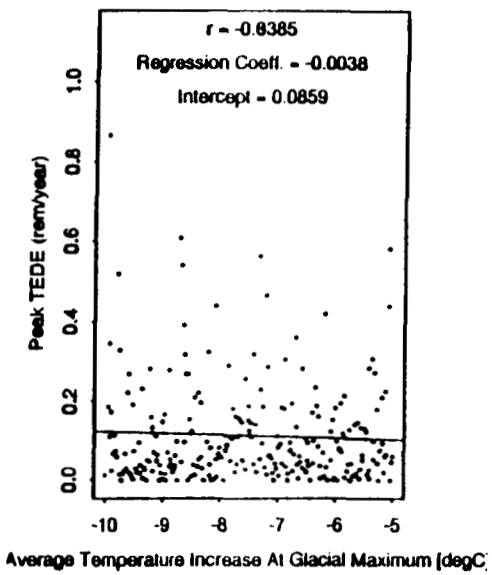
Parameter No. 1



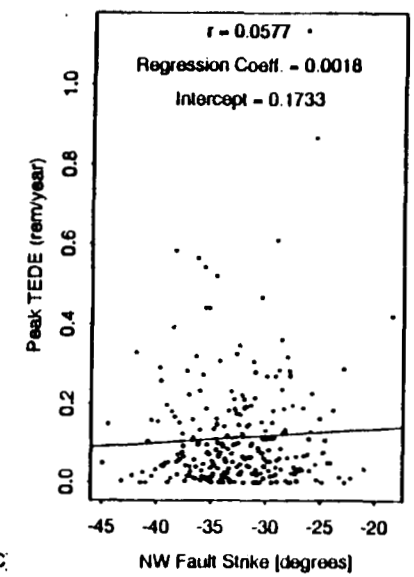
Parameter No. 2



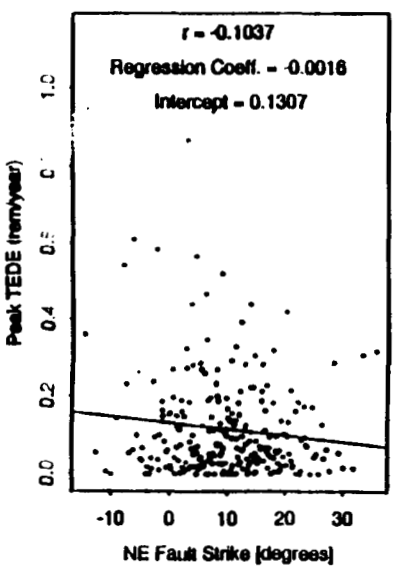
Parameter No. 3



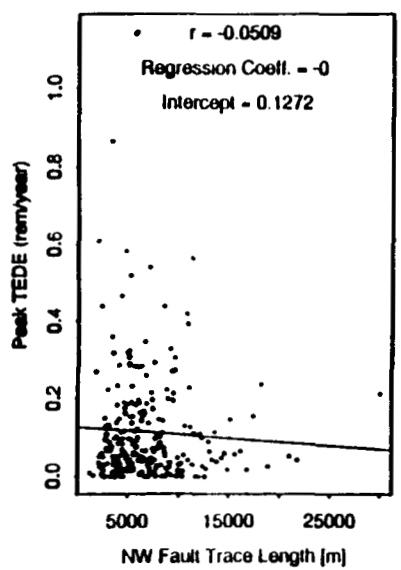
Parameter No. 5



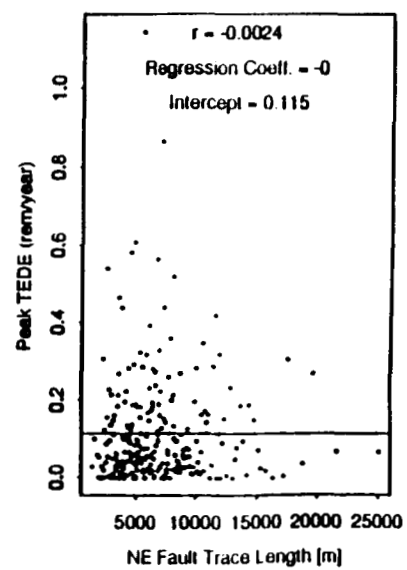
Parameter No. 6



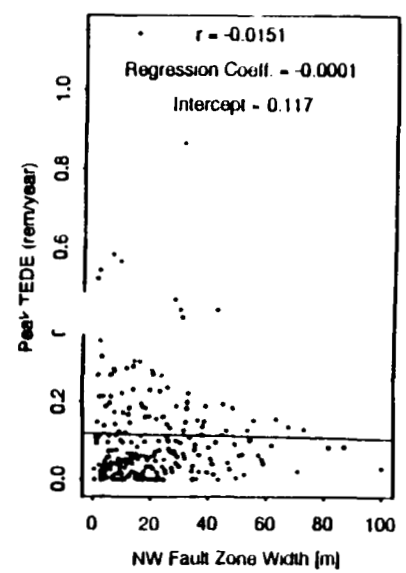
Parameter No. 7



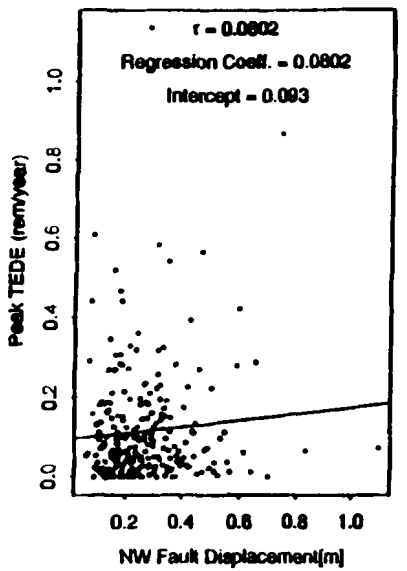
Parameter No. 8



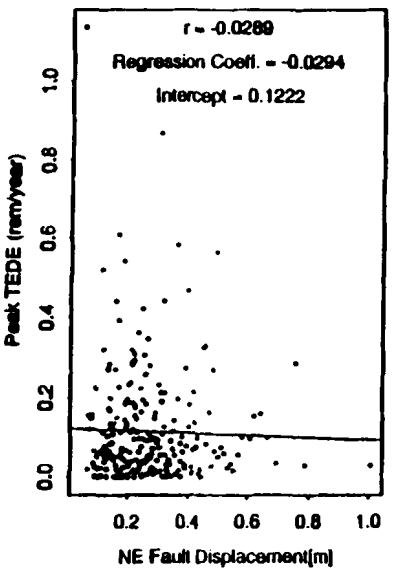
Parameter No. 9



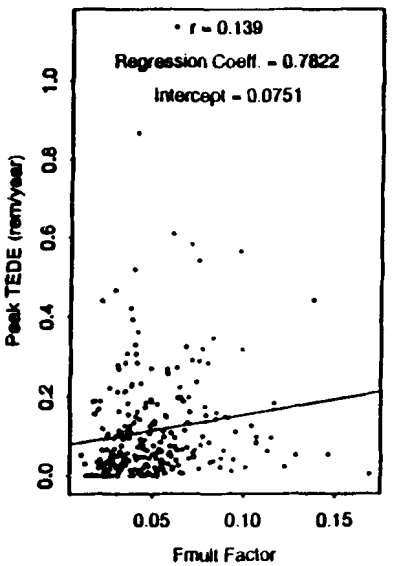
Parameter No. 11



Parameter No. 12



Parameter No. 14



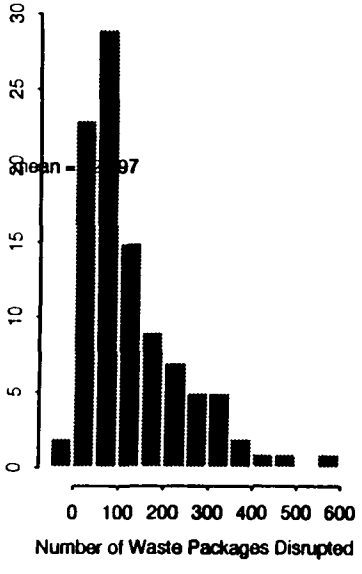
APPENDIX C

Run: FLTO_Run2

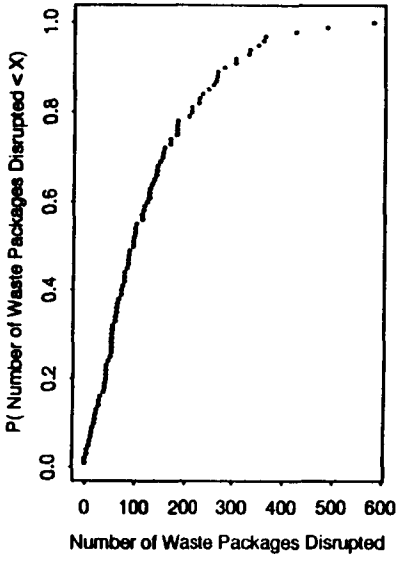
Distance to Critical Group = 5 km
Recurrence Interval = 50,000 yr
Only FAULTO, Uniform Corrosion, Backfill

5 km Scenario
Summary Plots for Number of Waste Packages Disrupted

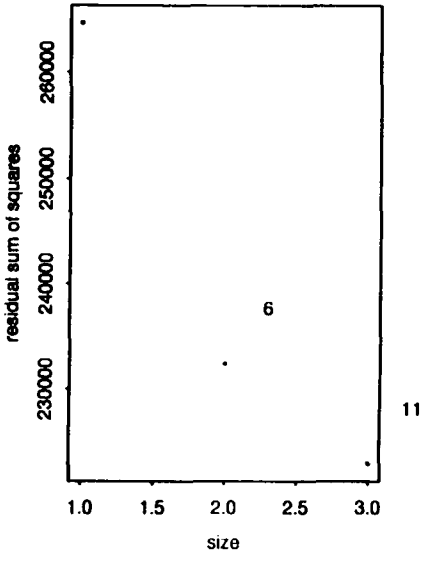
Frequency Distribution



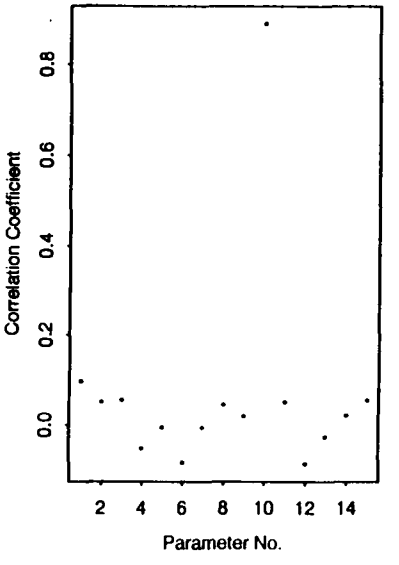
Cumulative Frequency



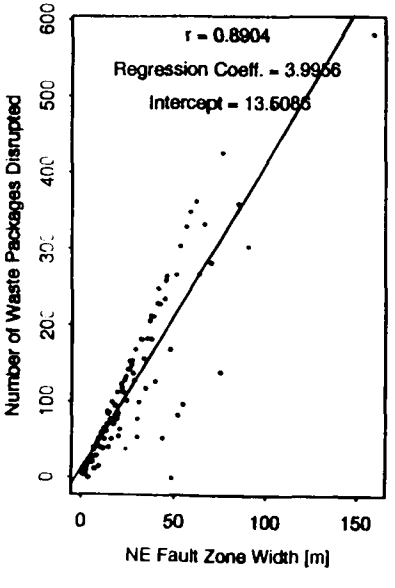
Stepwise Reduction in Error



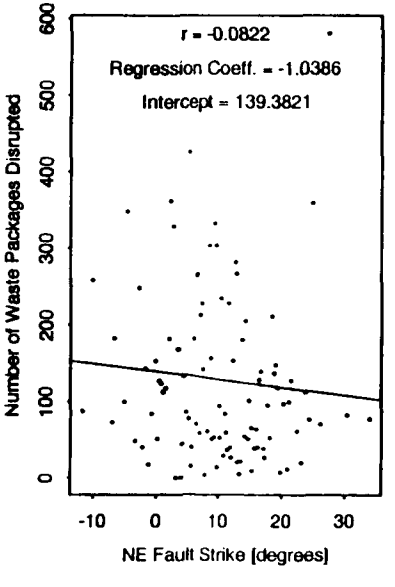
Correlation Coefficients
Parameter ~ Number of WP Disrupted



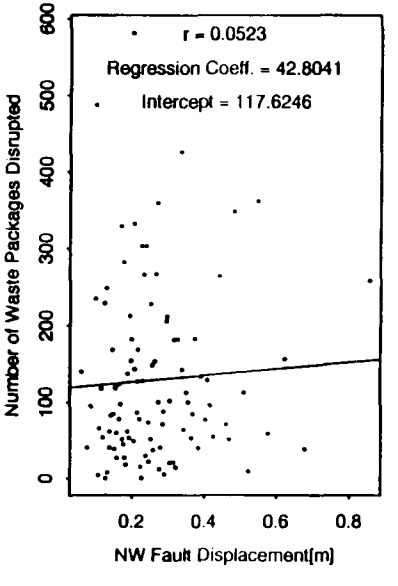
Parameter No. 10



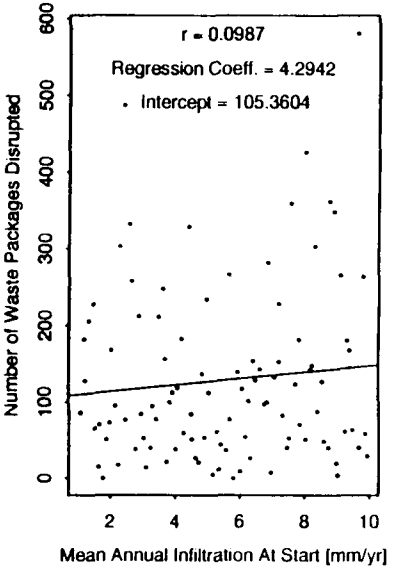
Parameter No. 6



Parameter No. 11

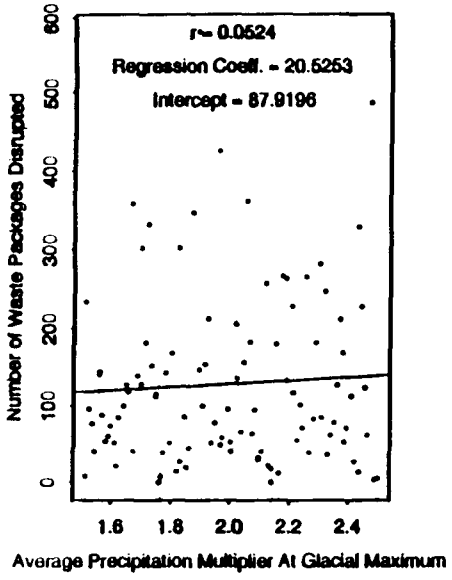


Parameter No. 1

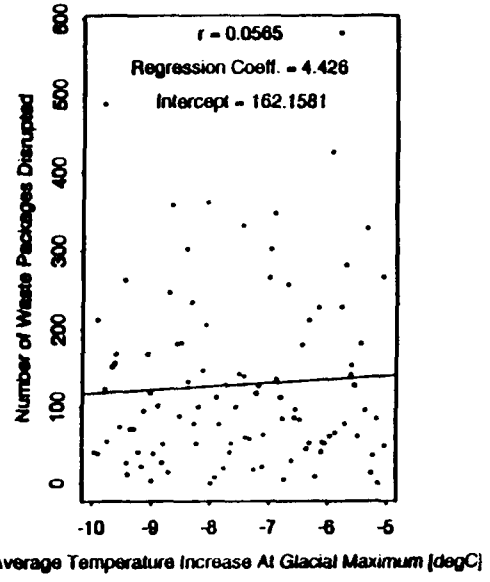


38/44

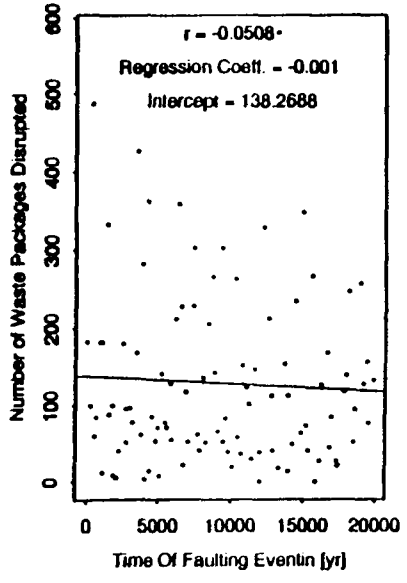
Parameter No. 2



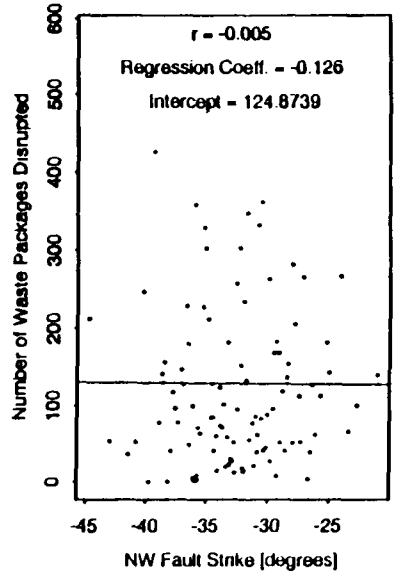
Parameter No. 3



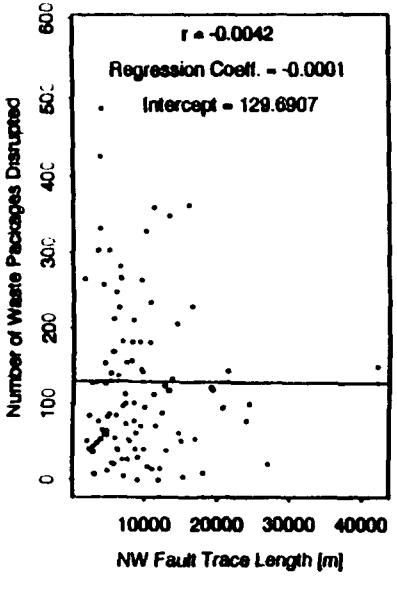
Parameter No. 4



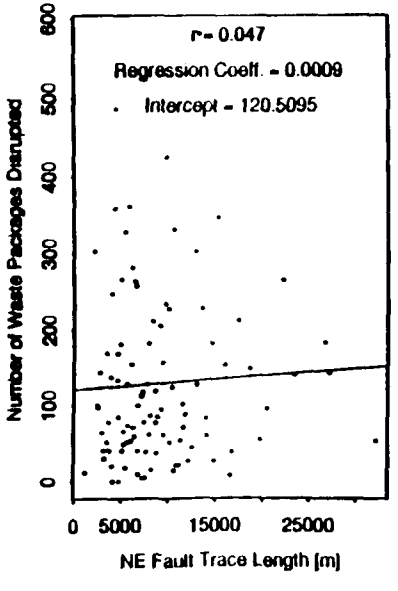
Parameter No. 5



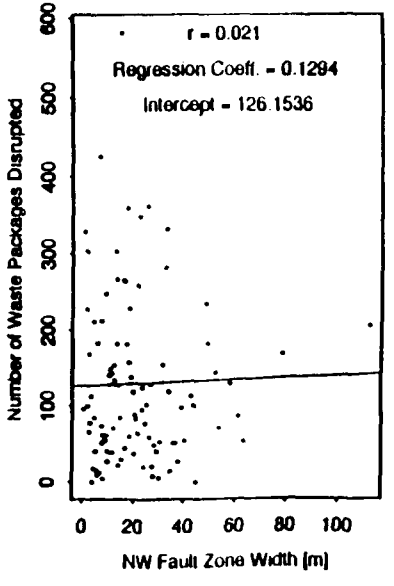
Parameter No. 7



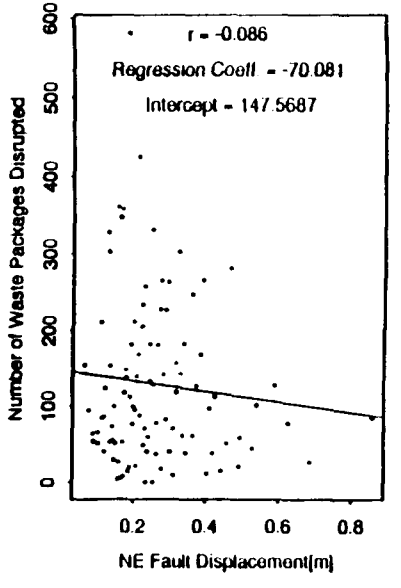
Parameter No. 8



Parameter No. 9

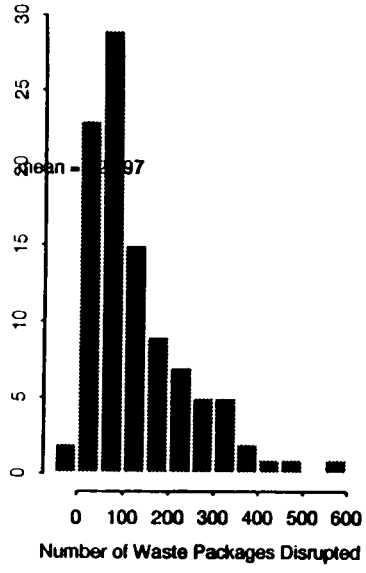


Parameter No. 12

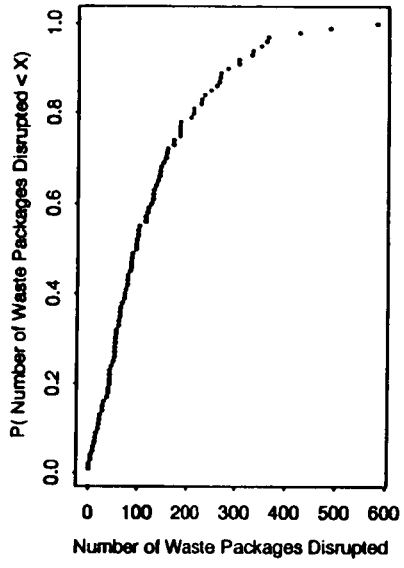


5 km Scenario
Summary Plots for Number of Waste Packages Disrupted

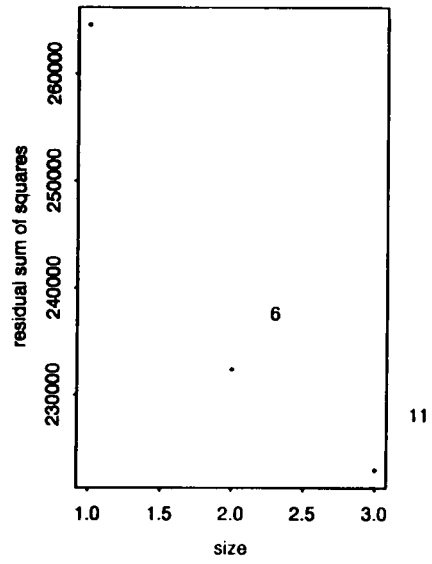
Frequency Distribution



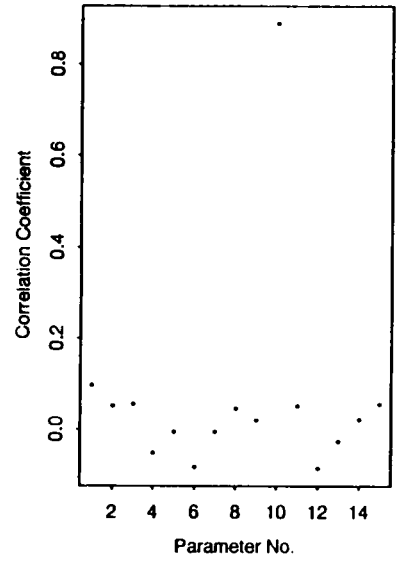
Cumulative Frequency



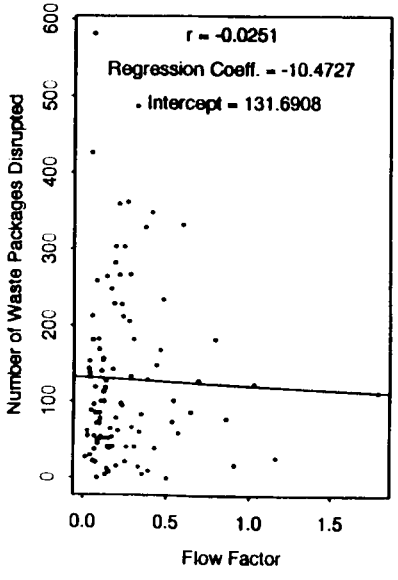
Stepwise Reduction in Error



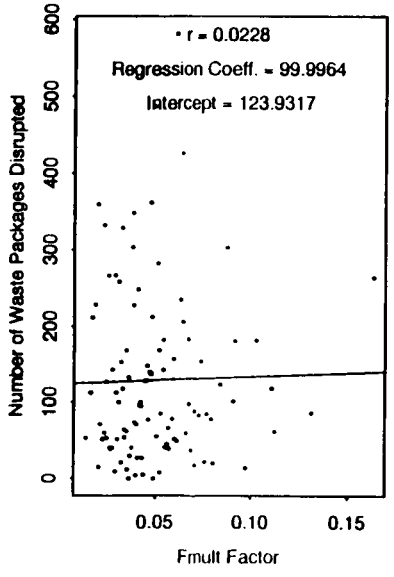
Correlation Coefficients
Parameter ~ Number of WP Disrupted



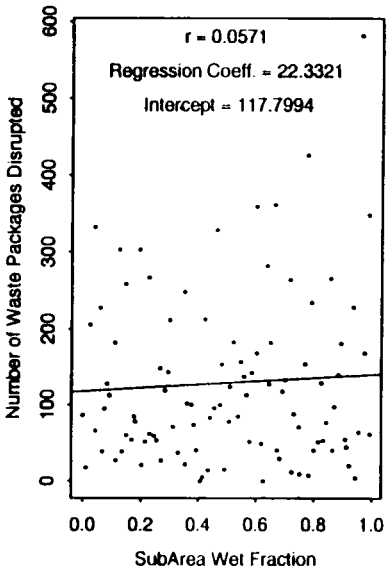
Parameter No. 13



Parameter No. 14

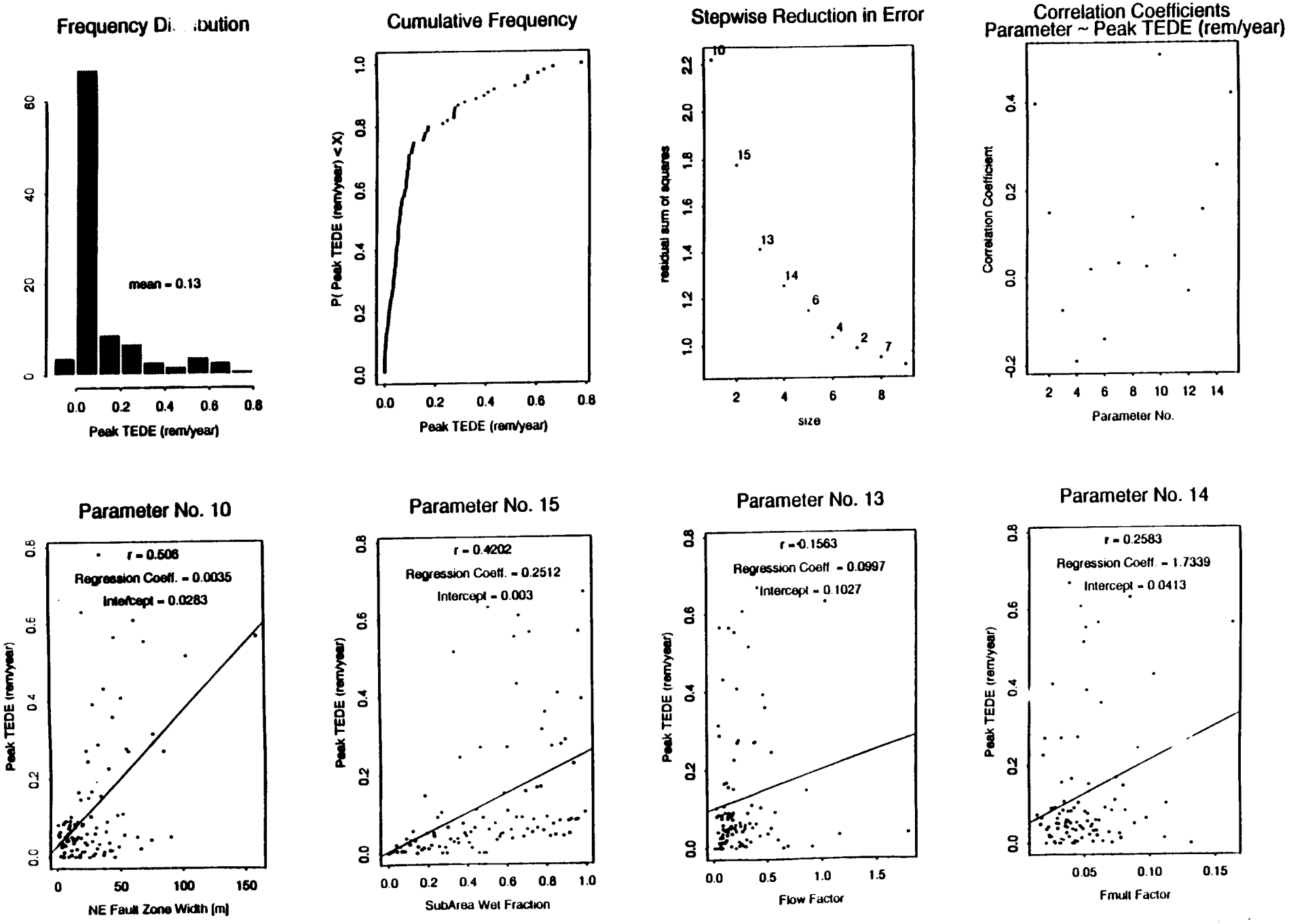


Parameter No. 15

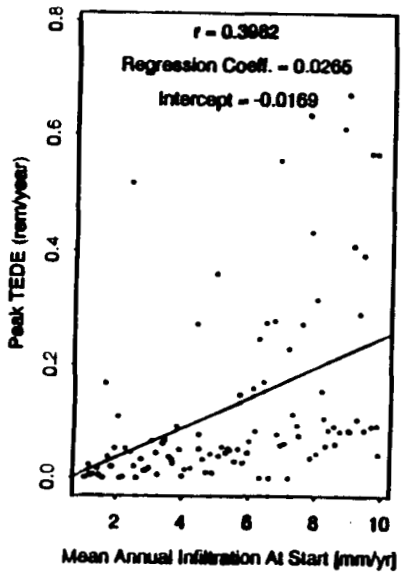


35/94

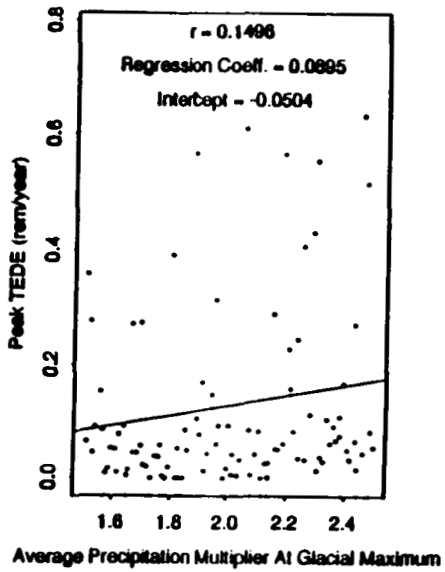
5 km Scenario
Summary Plots for Peak TEDE (rem/year)



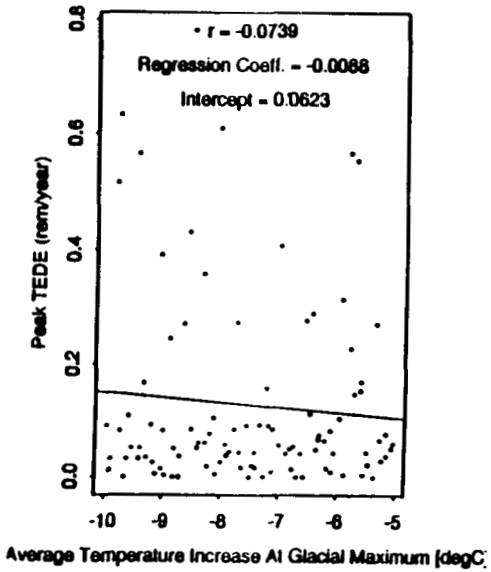
Parameter No. 1



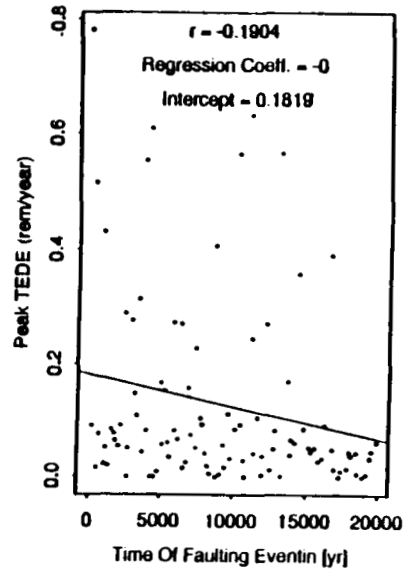
Parameter No. 2



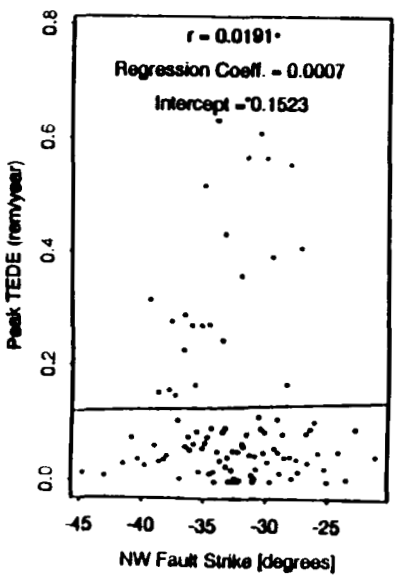
Parameter No. 3



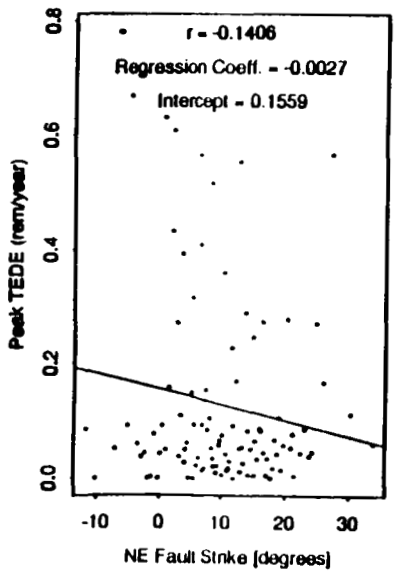
Parameter No. 4



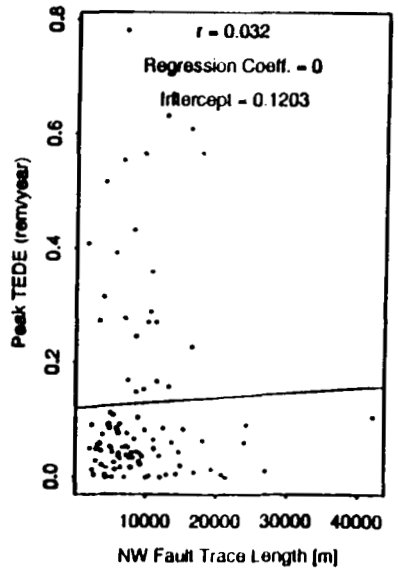
Parameter No. 5



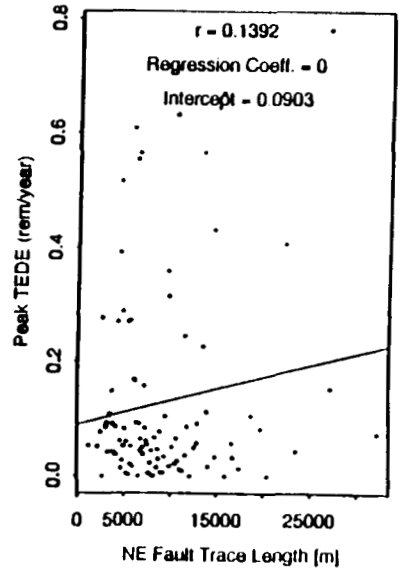
Parameter No. 6



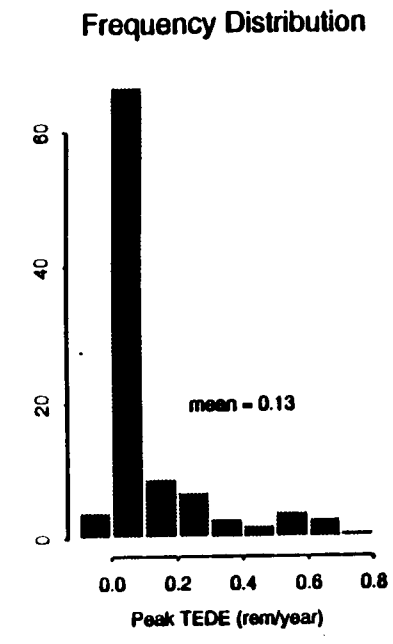
Parameter No. 7

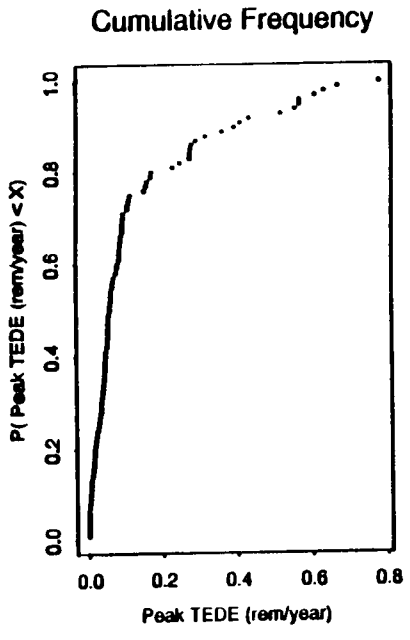


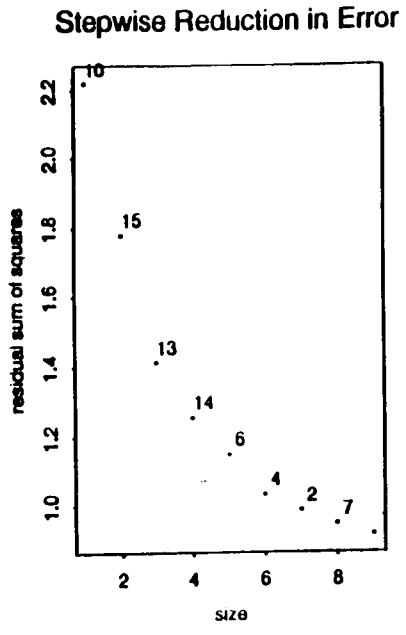
Parameter No. 8

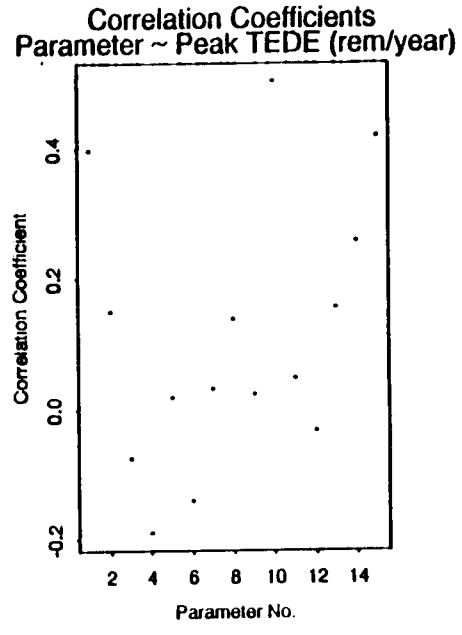


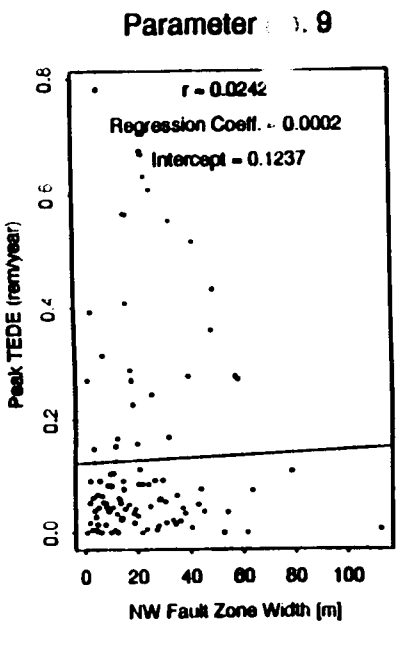
5 km Scenario
Summary Plots for Peak TEDE (rem/year)

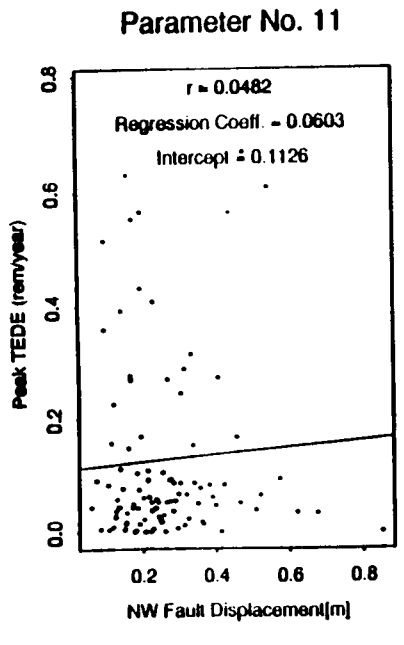


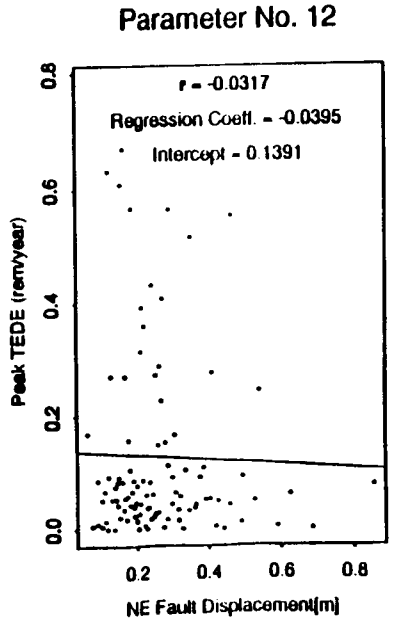




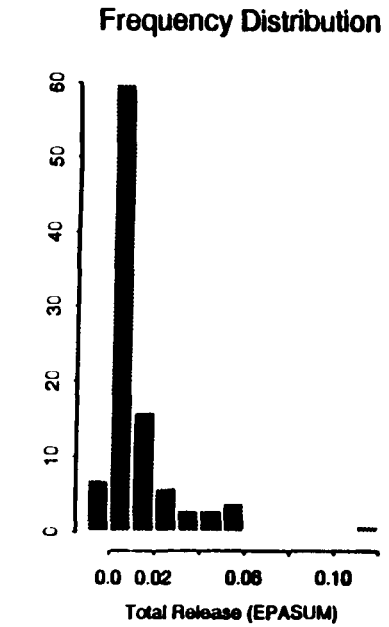


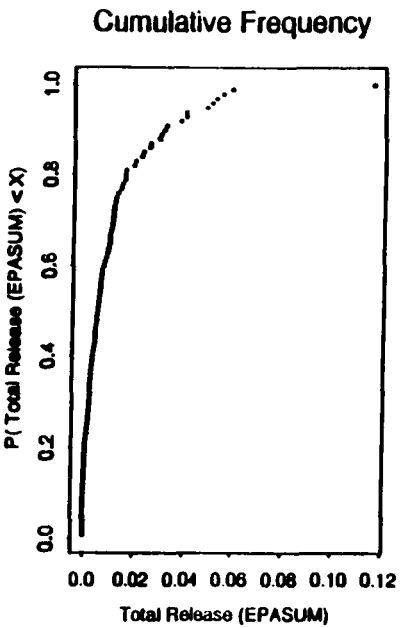


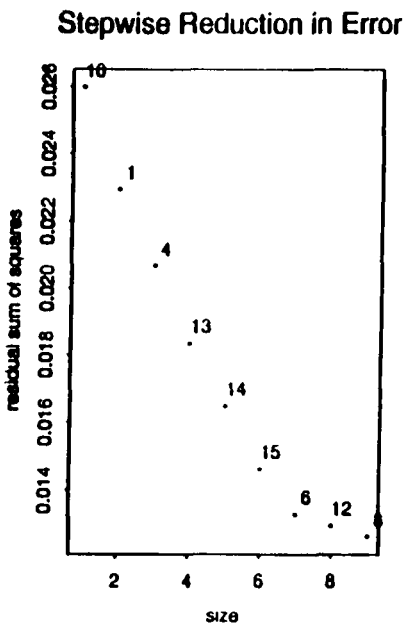


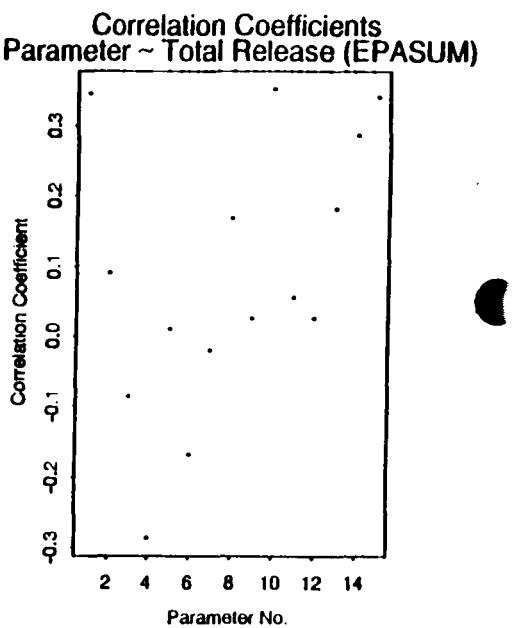


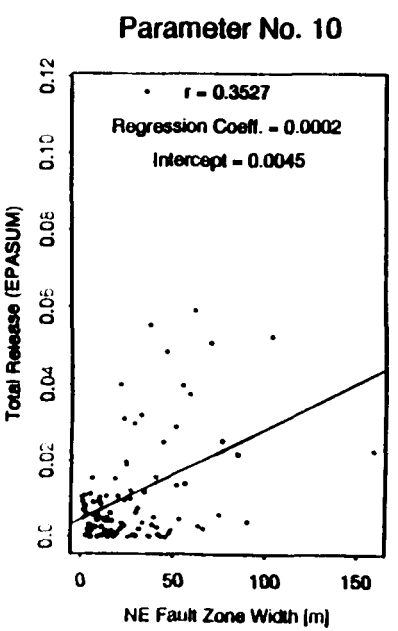
5 km Scenario
Summary Plots for Total Release (EPASUM)

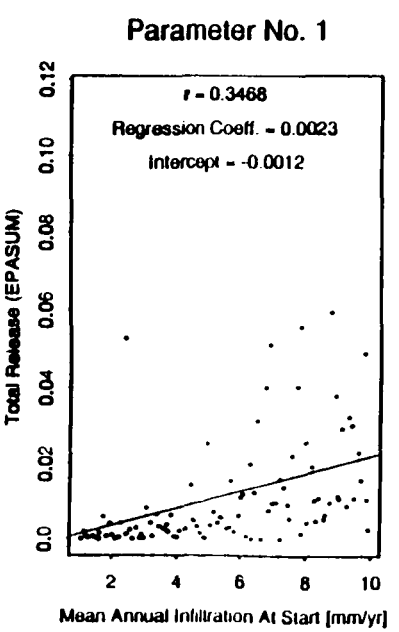


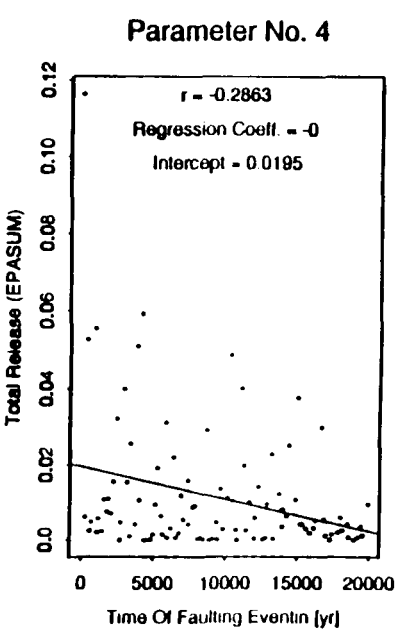


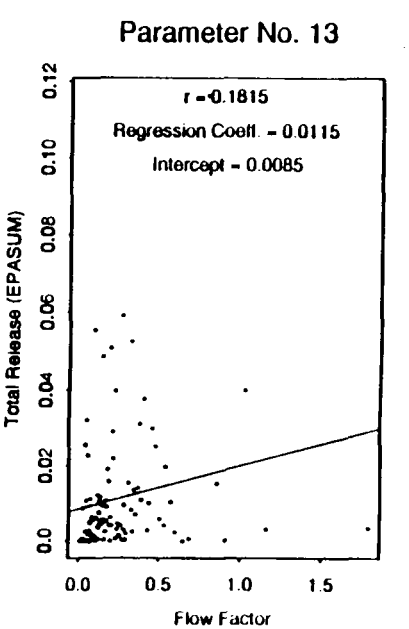




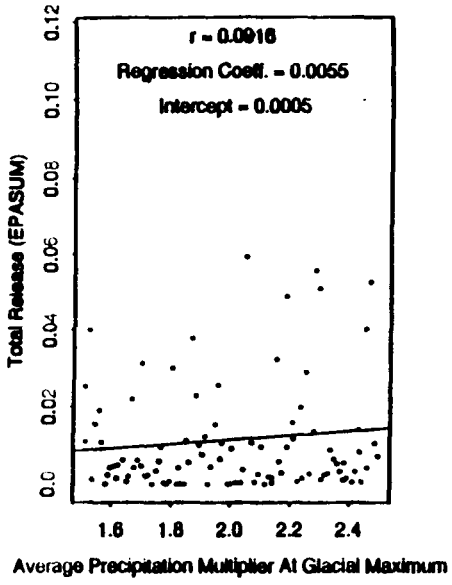




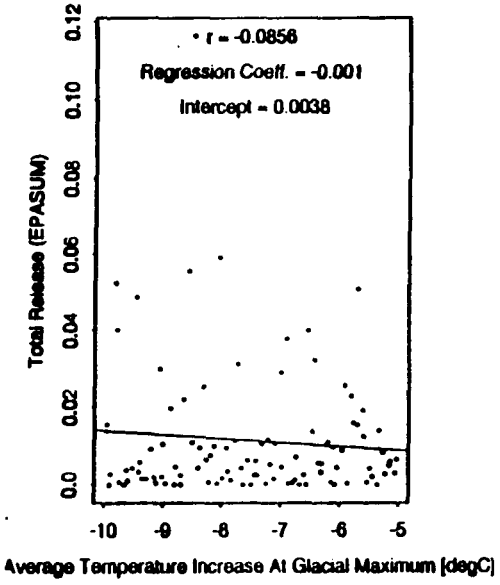




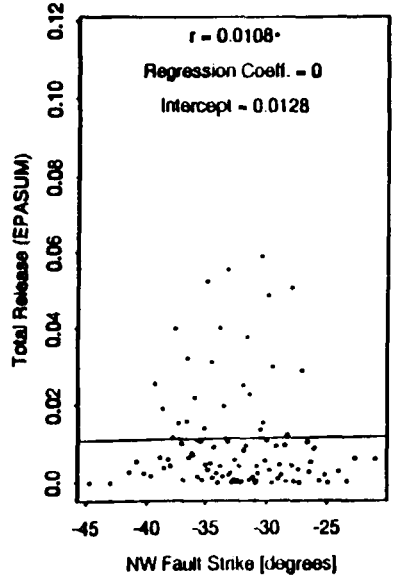
Parameter No. 2



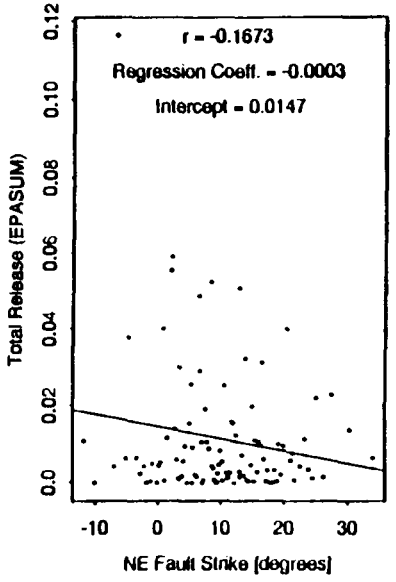
Parameter No. 3



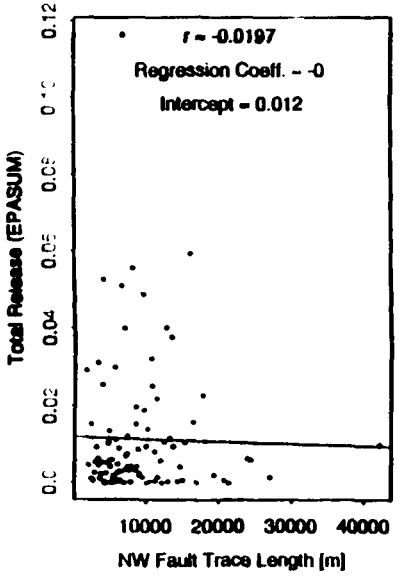
Parameter No. 5



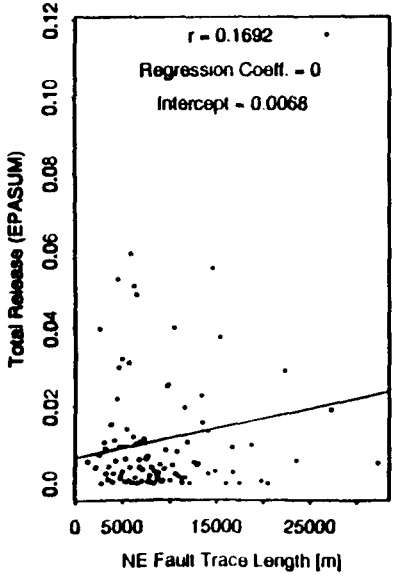
Parameter No. 6



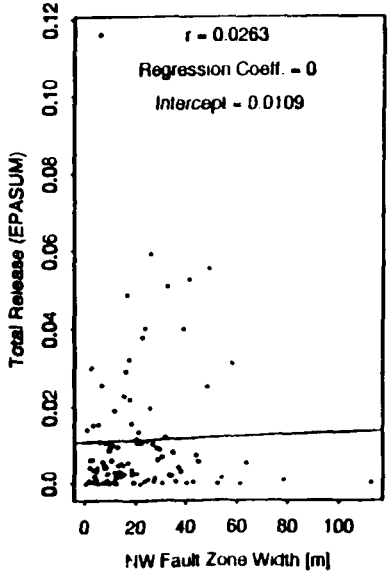
Parameter No. 7



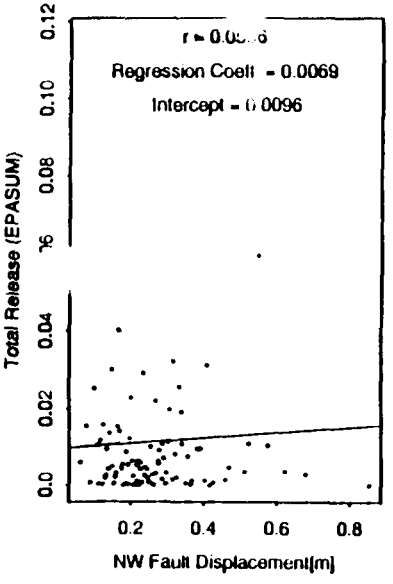
Parameter No. 8



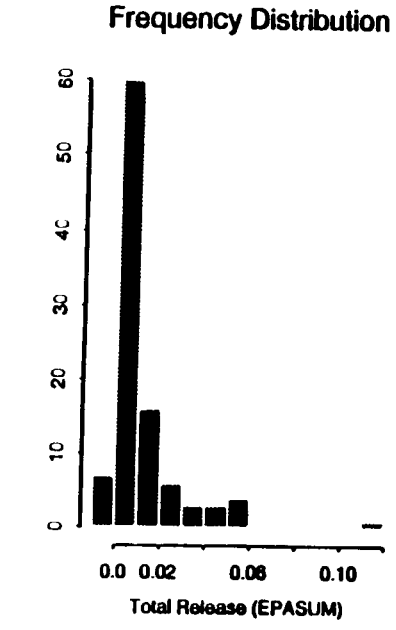
Parameter No. 9

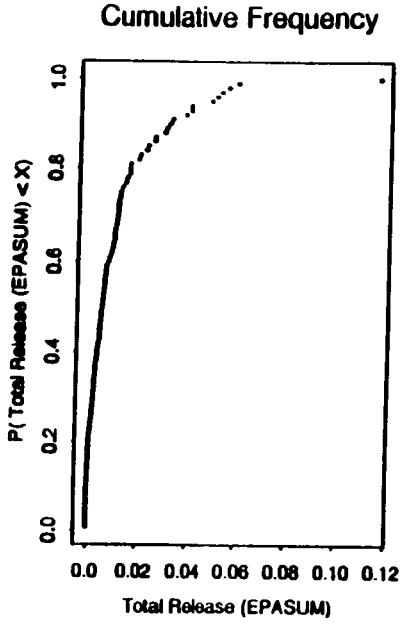


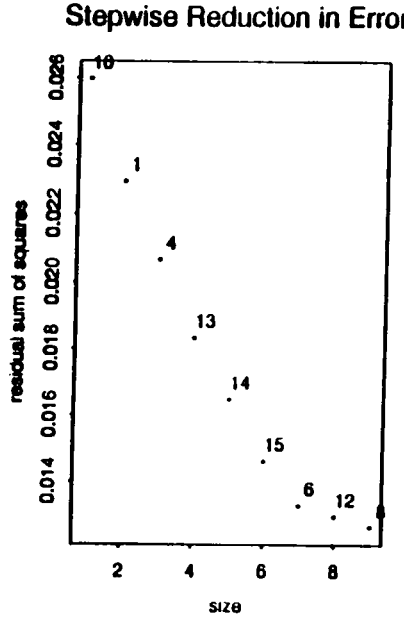
Parameter No. 11

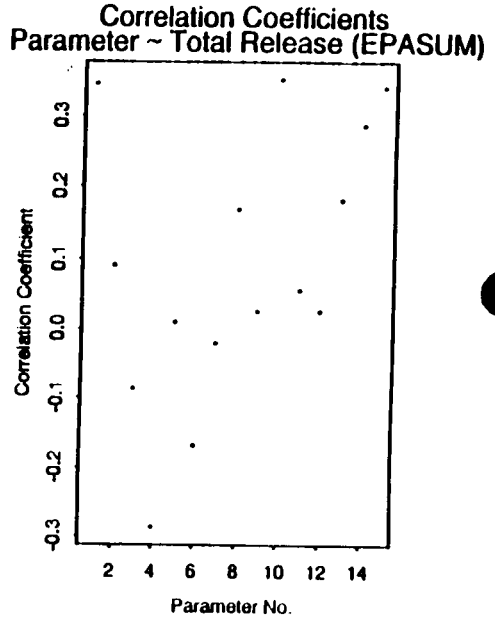


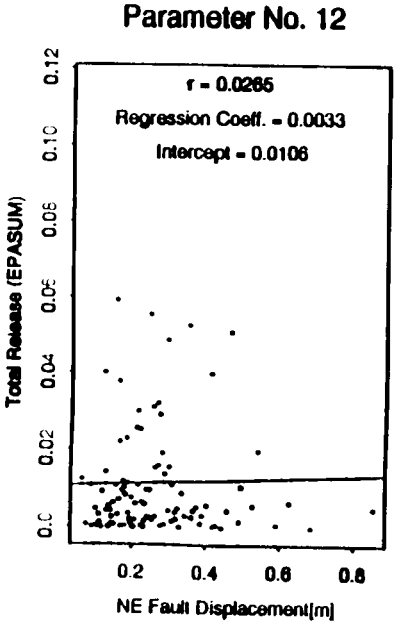
5 km Scenario
Summary Plots for Total Release (EPASUM)

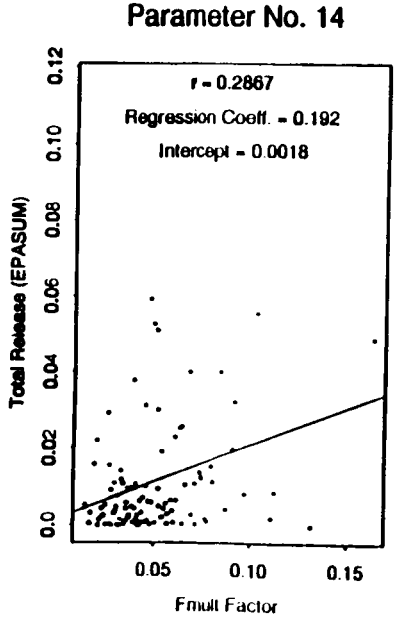


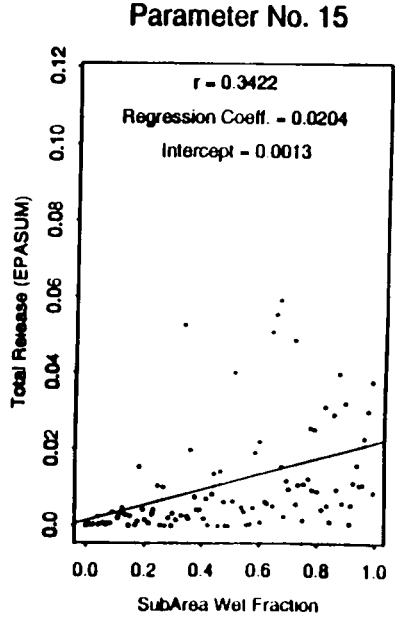












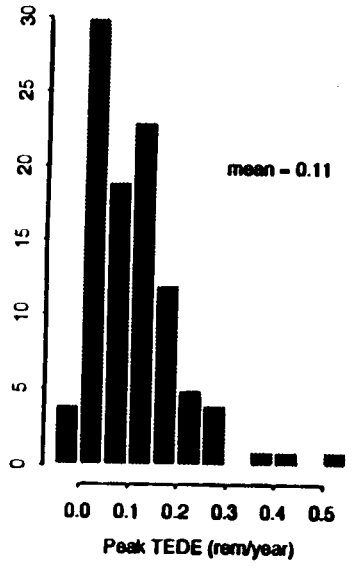
43/44

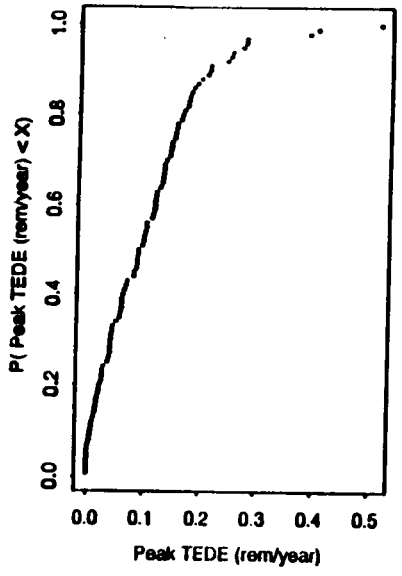
APPENDIX D

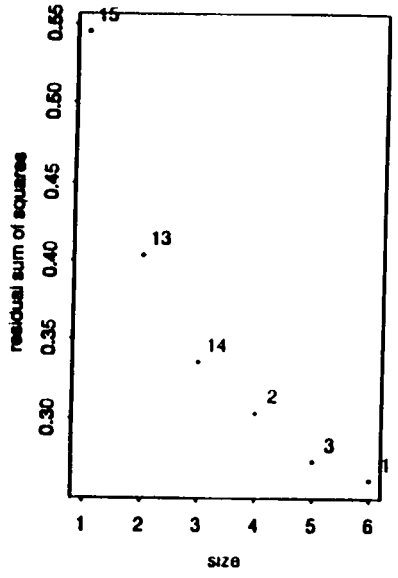
Run: FLTO_Run3

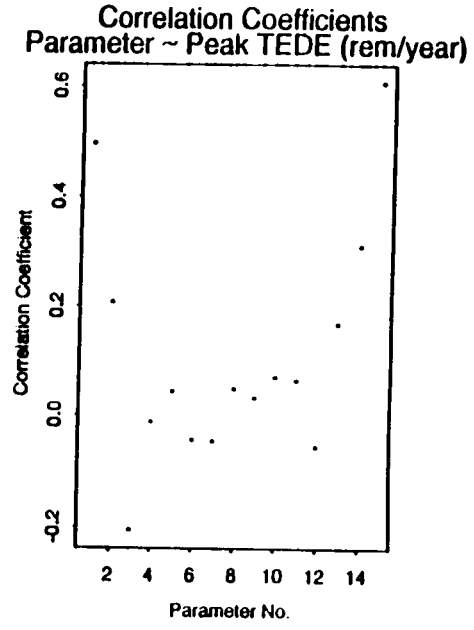
Distance to Critical Group = 5 km
Only SEISMO, Uniform Corrosion, Backfill

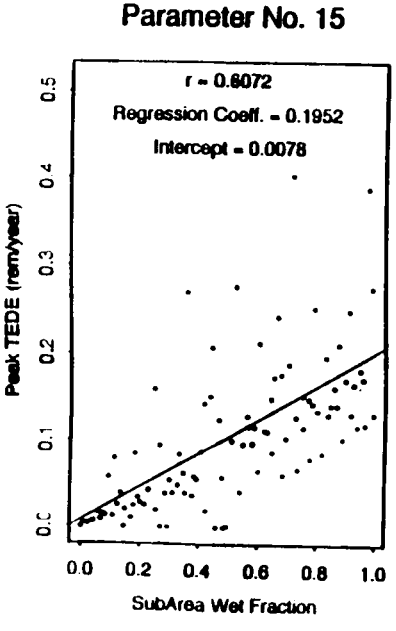
5 km Scenario
Summary Plots for Peak TEDE (rem/year)

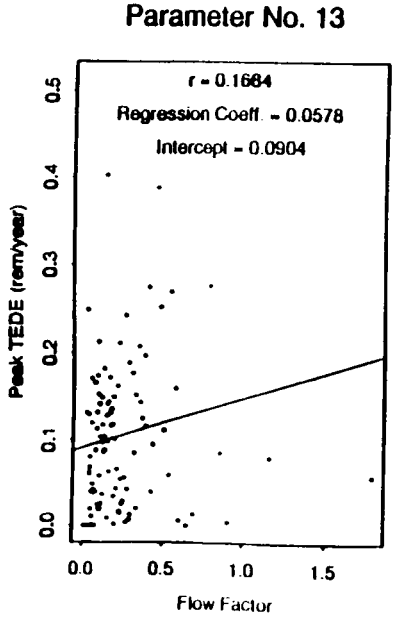


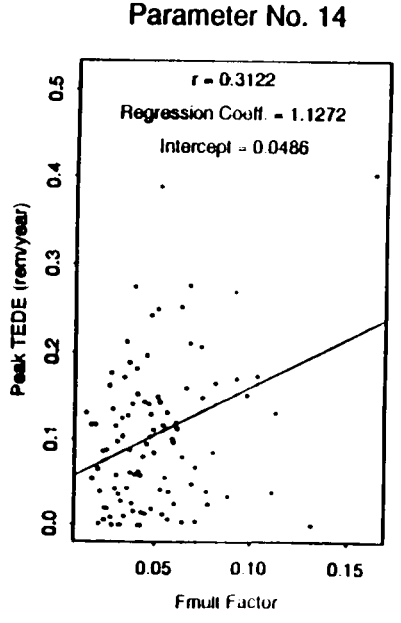


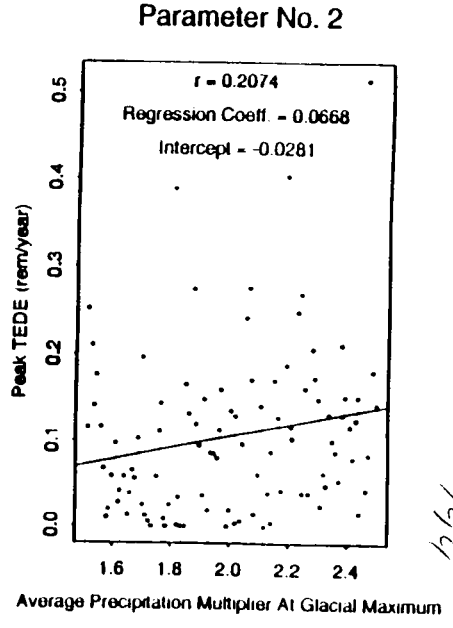




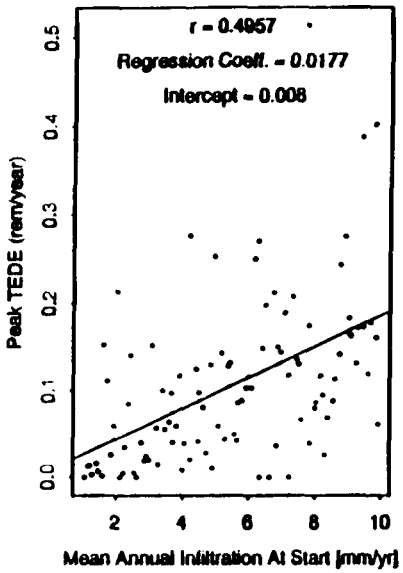




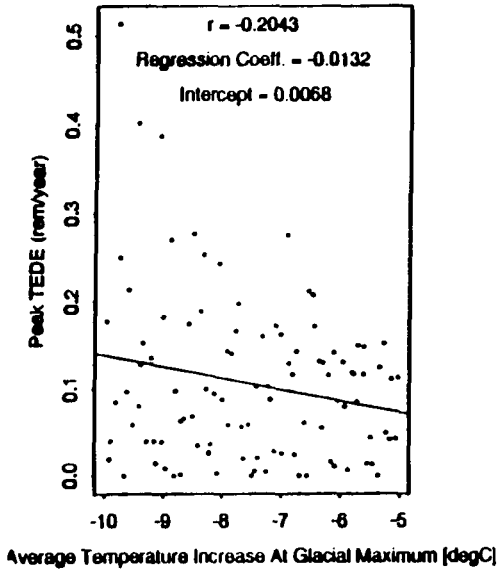




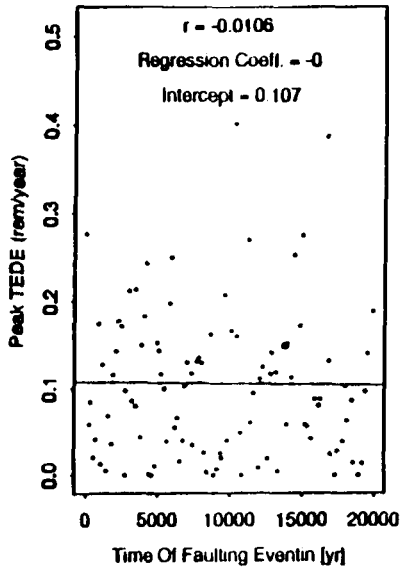
Parameter No. 1



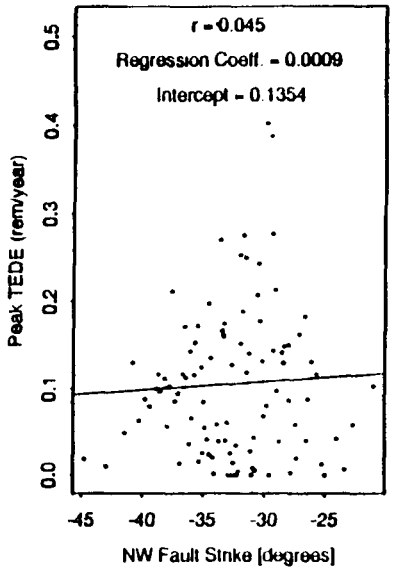
Parameter No. 3



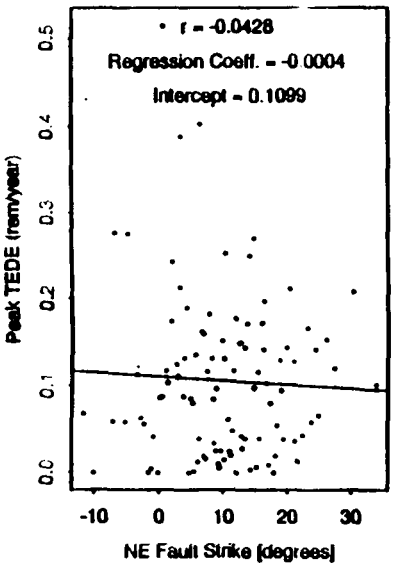
Parameter No. 4



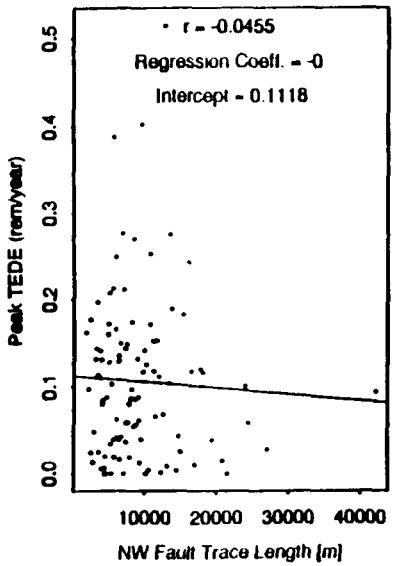
Parameter No. 5



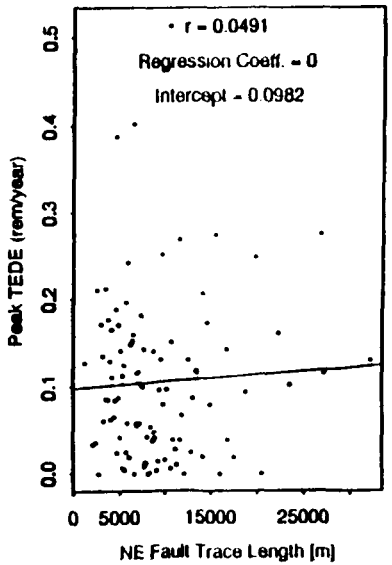
Parameter No. 6



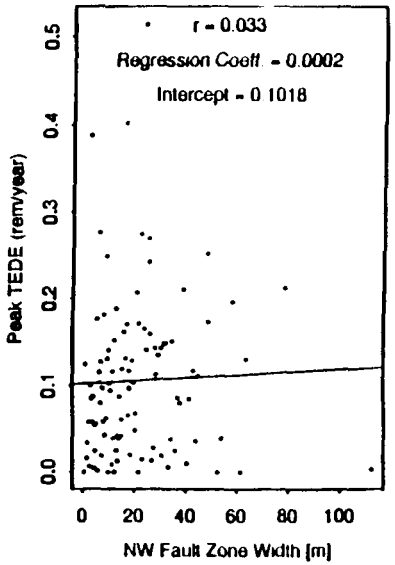
Parameter No. 7



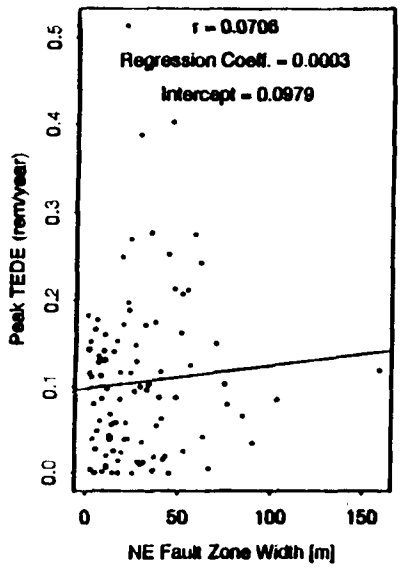
Parameter No. 8



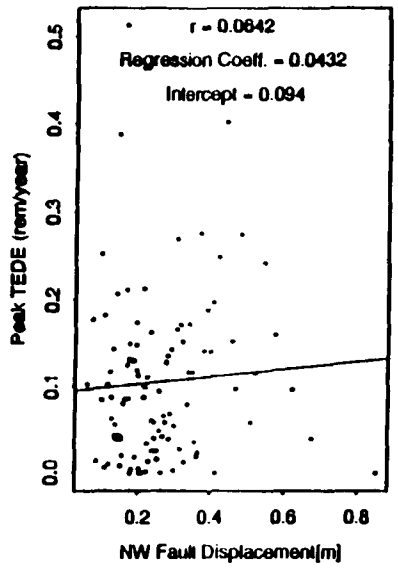
Parameter No. 9



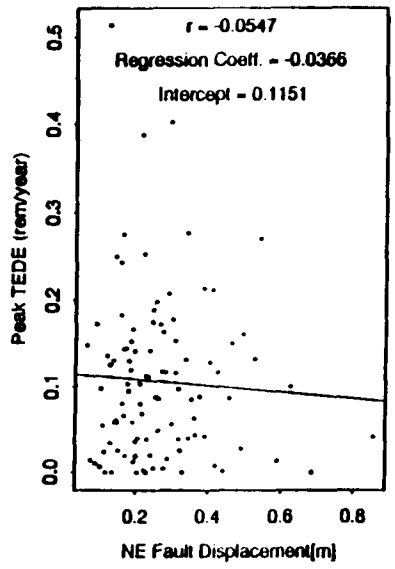
Parameter No. 10



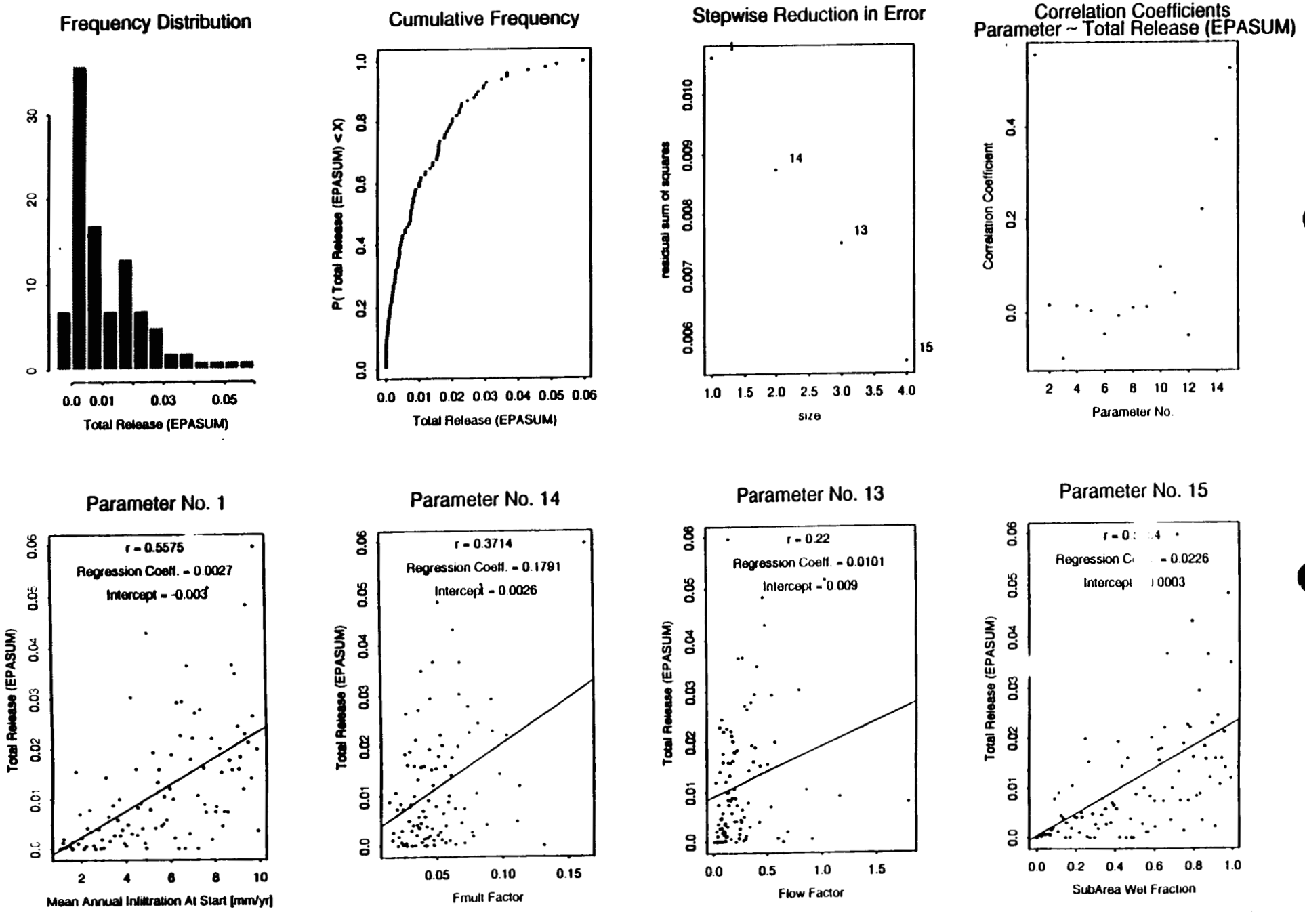
Parameter No. 11



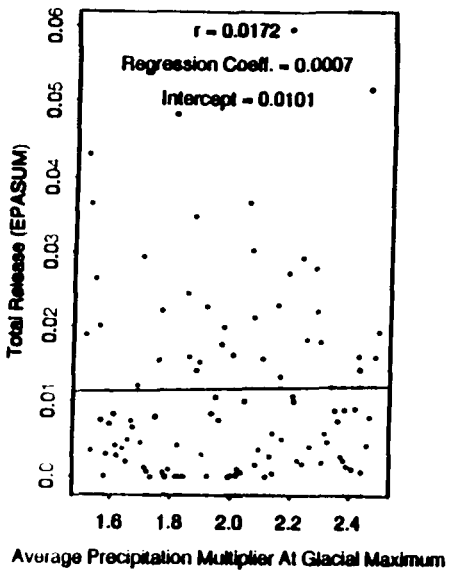
Parameter No. 12



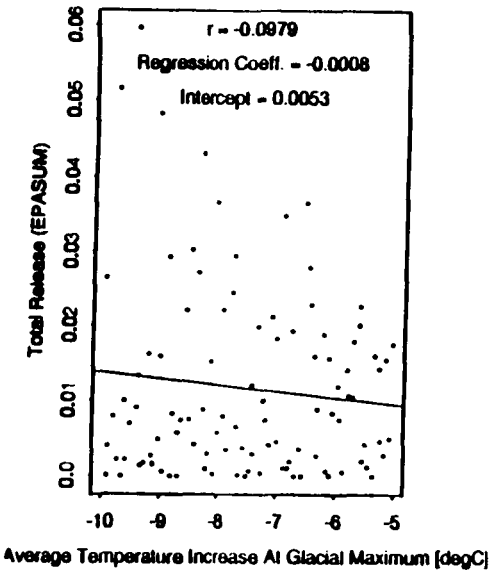
5 km Scenario
Summary Plots for Total Release (EPASUM)



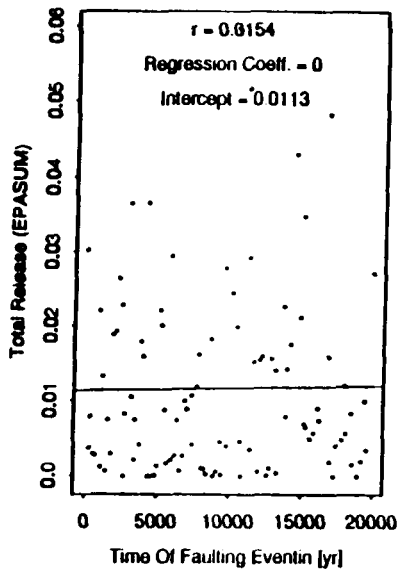
Parameter No. 2



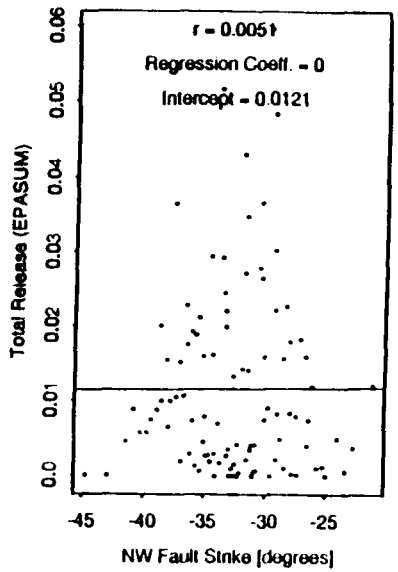
Parameter No. 3



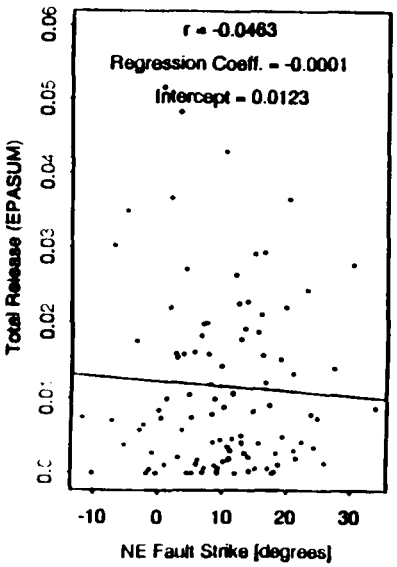
Parameter No. 4



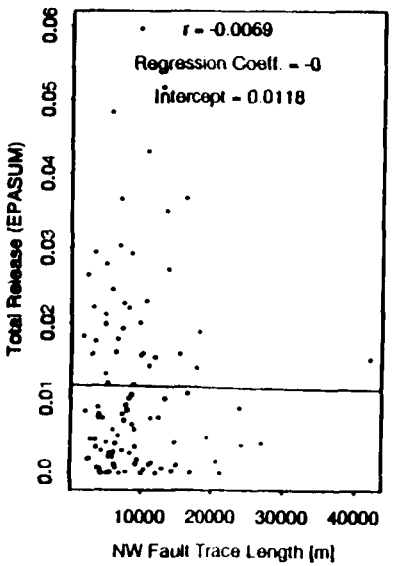
Parameter No. 5



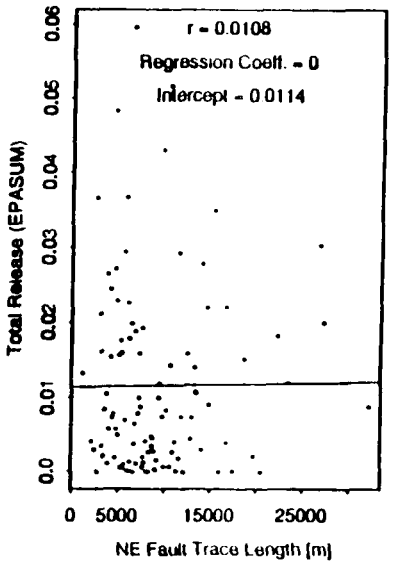
Parameter No. 6



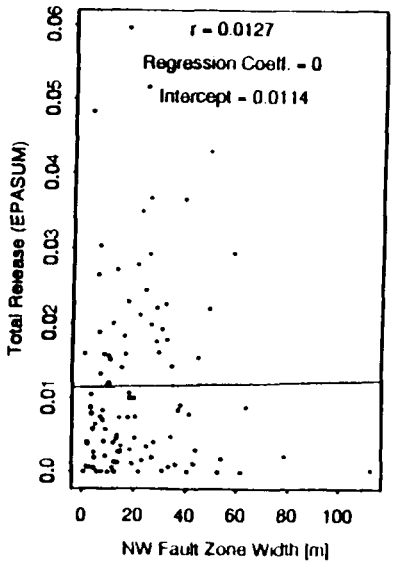
Parameter No. 7



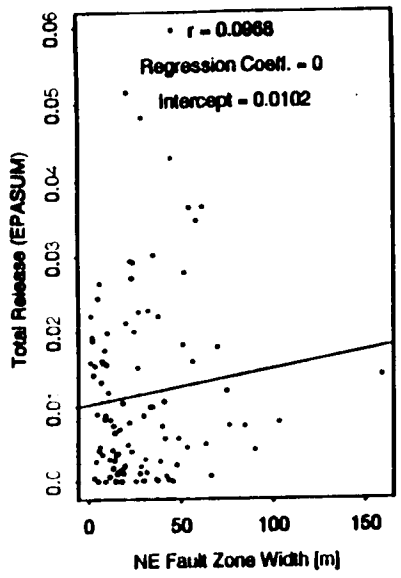
Parameter No. 8



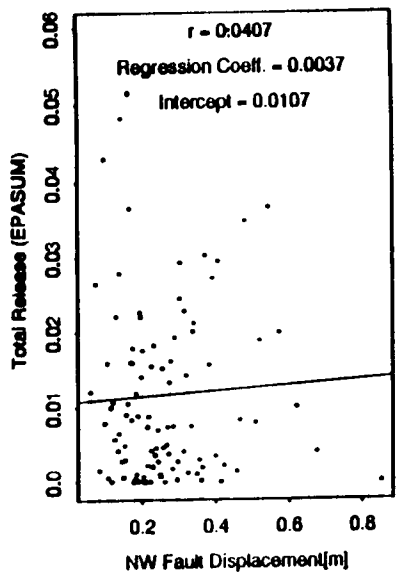
Parameter No. 9



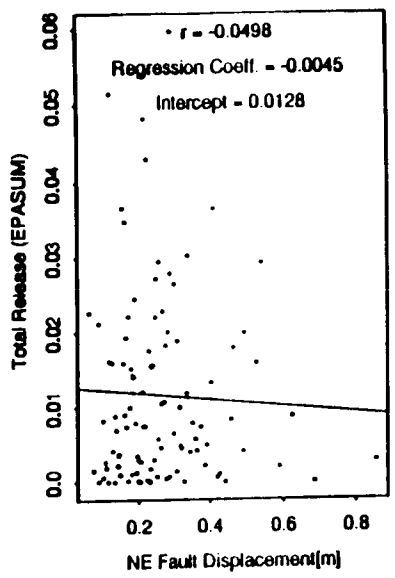
Parameter No. 10



Parameter No. 11



Parameter No. 12



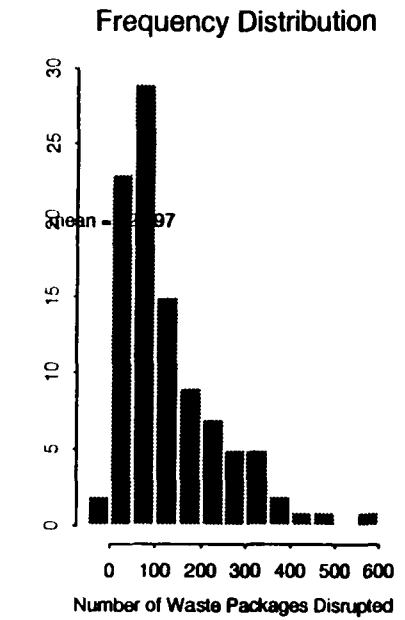
47/94

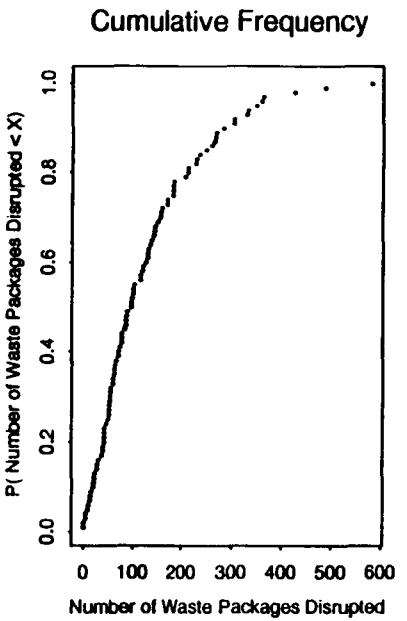
APPENDIX E

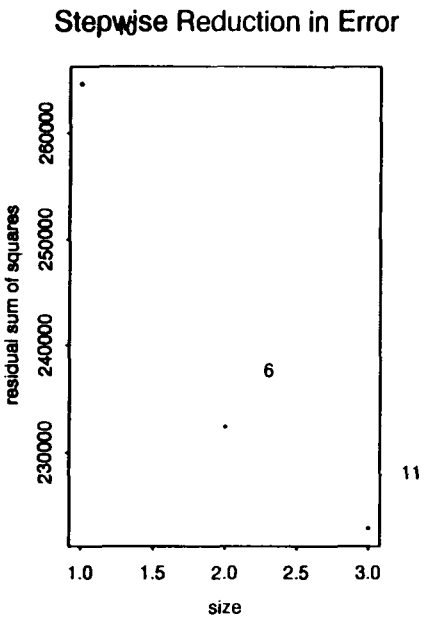
Run: FLTO_Run4

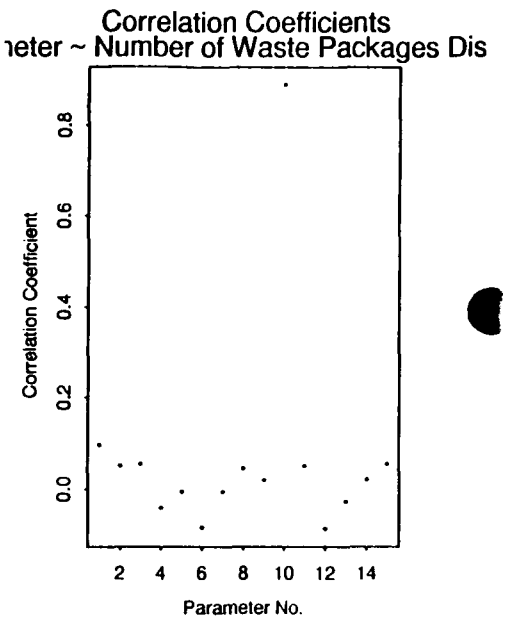
Distance to Critical Group = 5 km
Recurrence Interval = 5,000 yr
Only FAULTO, Uniform Corrosion, Backfill

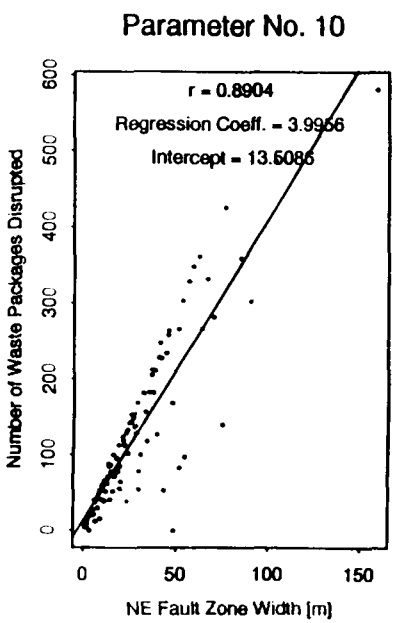
5 km Scenario
Summary Plots for Number of Waste Packages Disrupted

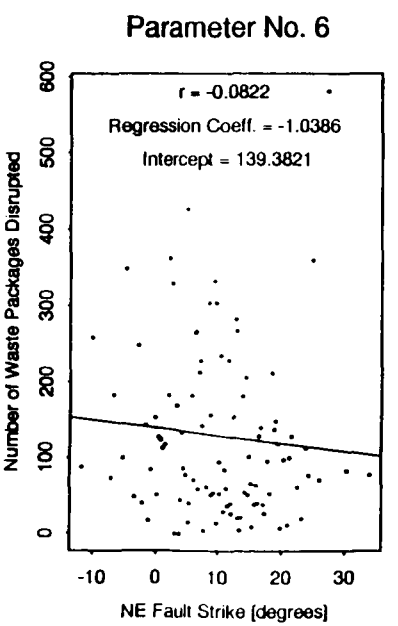


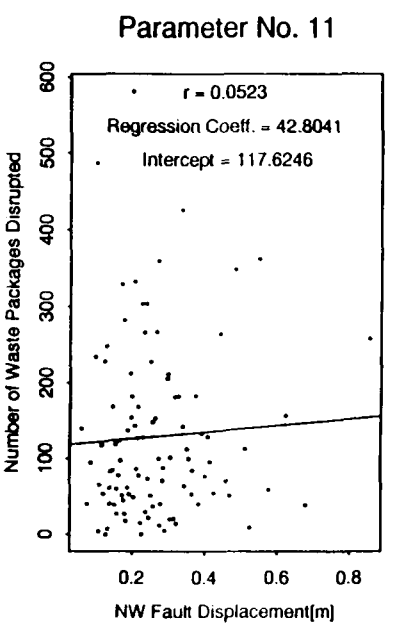


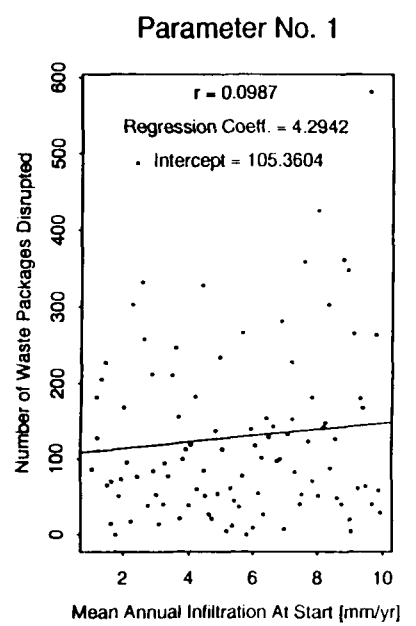




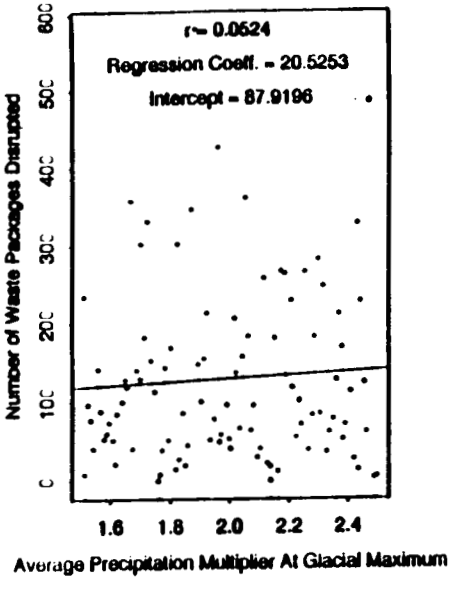




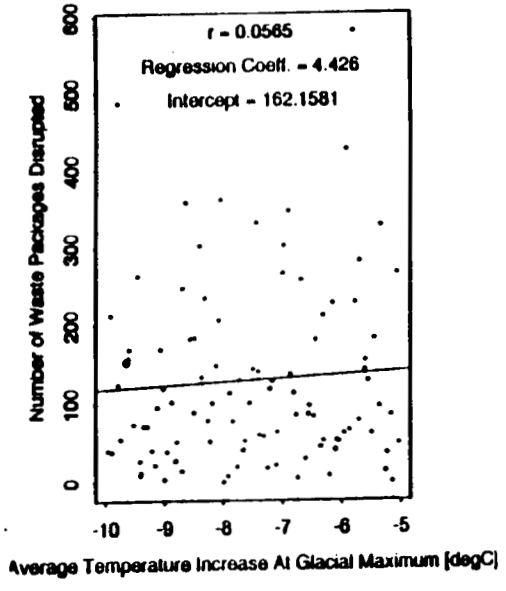




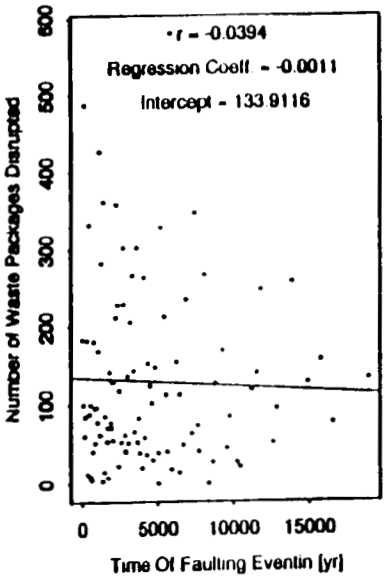
Parameter No. 2



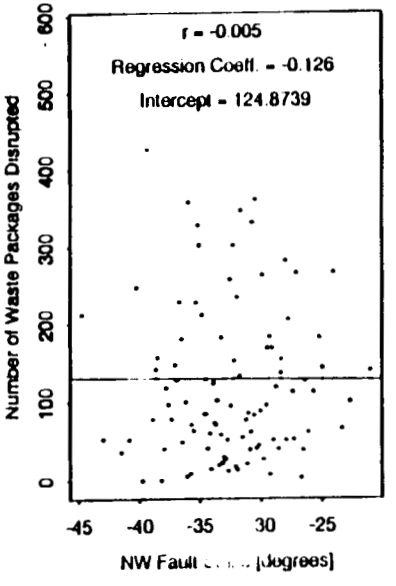
Parameter No. 3



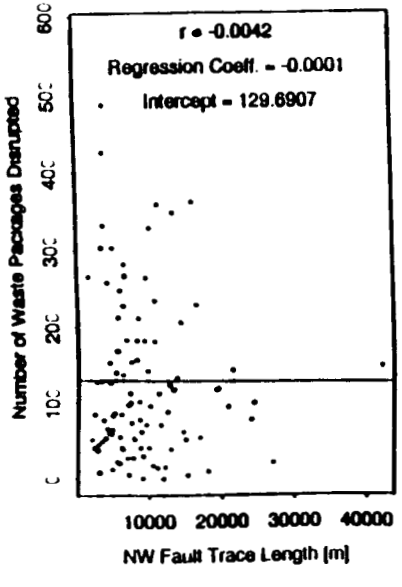
Parameter No. 4



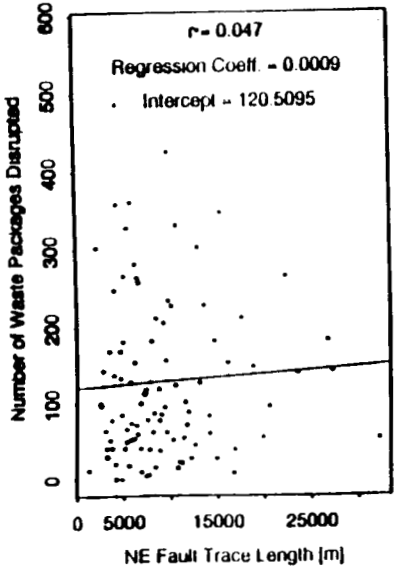
Parameter No. 5



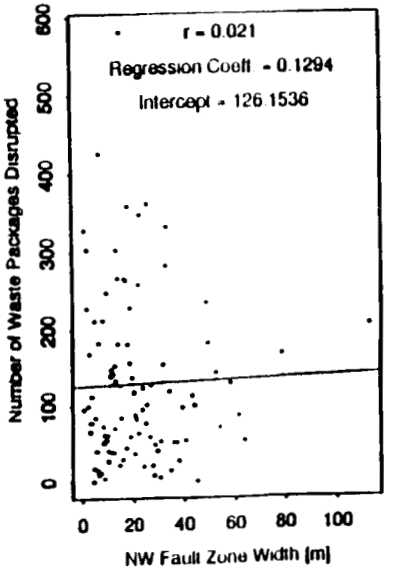
Parameter No. 7



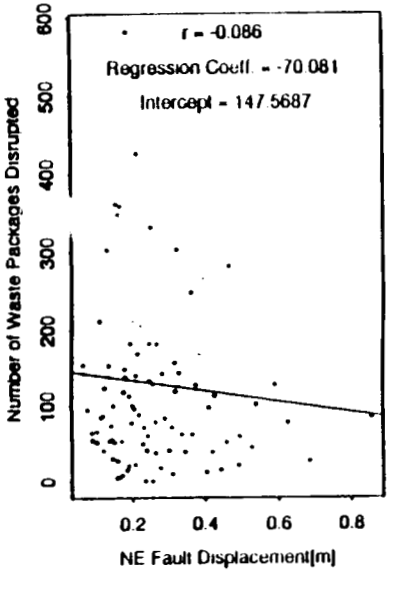
Parameter No. 8



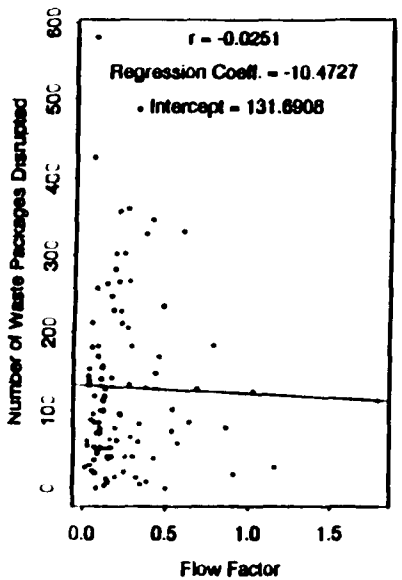
Parameter No. 9



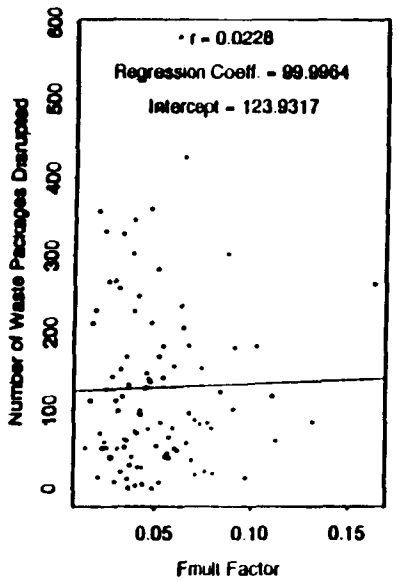
Parameter No. 12



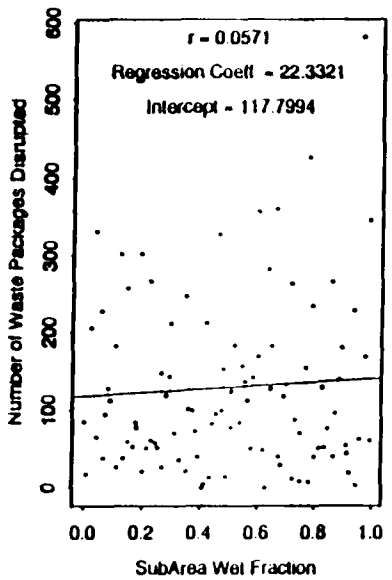
Parameter No. 13



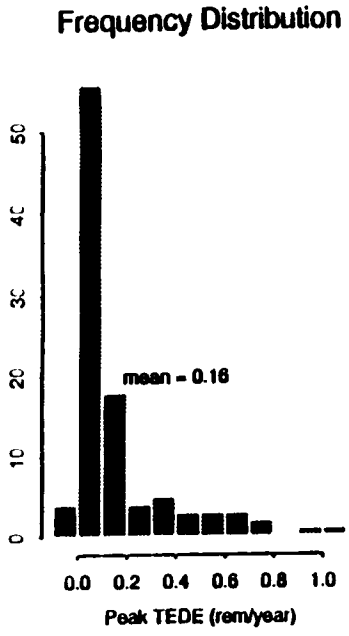
Parameter No. 14

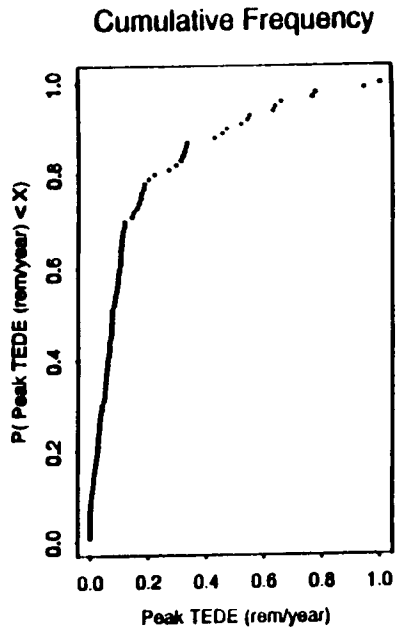


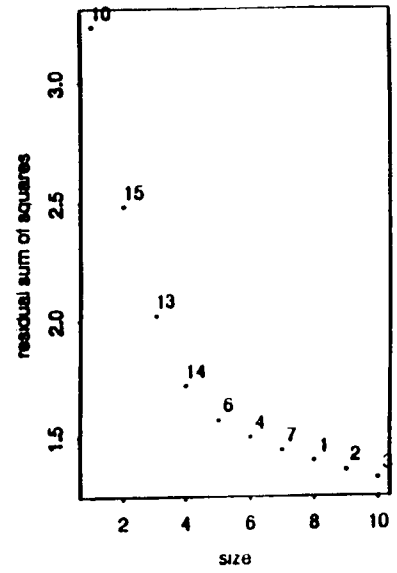
Parameter No. 15

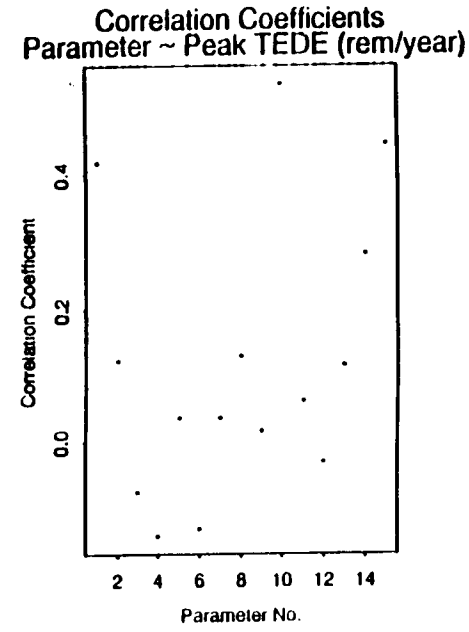


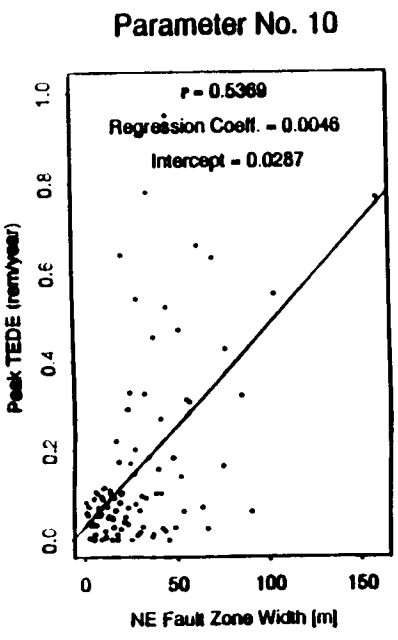
5 km Scenario
Summary Plots for Peak TEDE (rem/year)

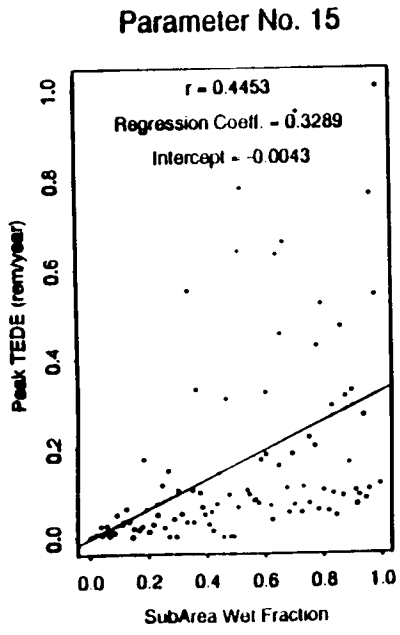


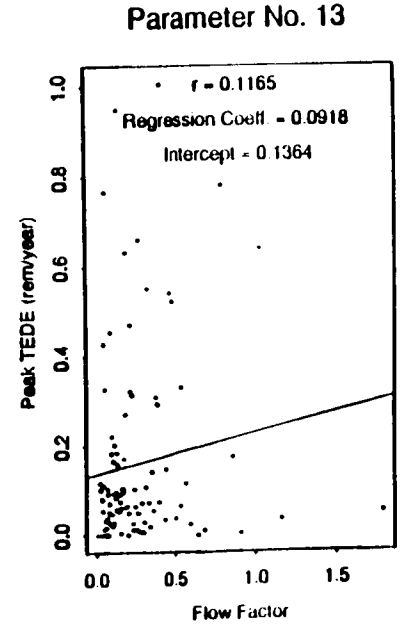


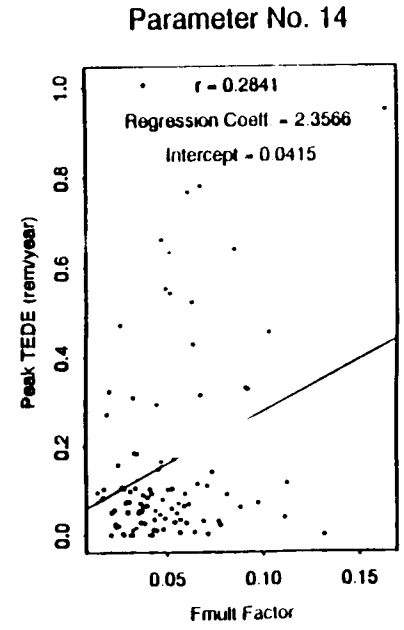






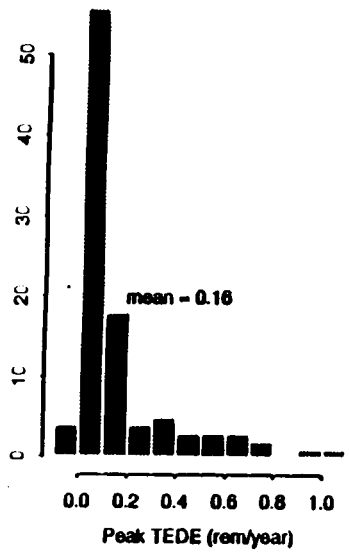




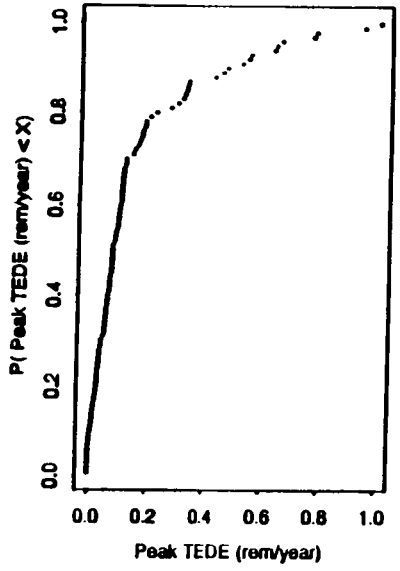


5 km Scenario
Summary Plots for Peak TEDE (rem/year)

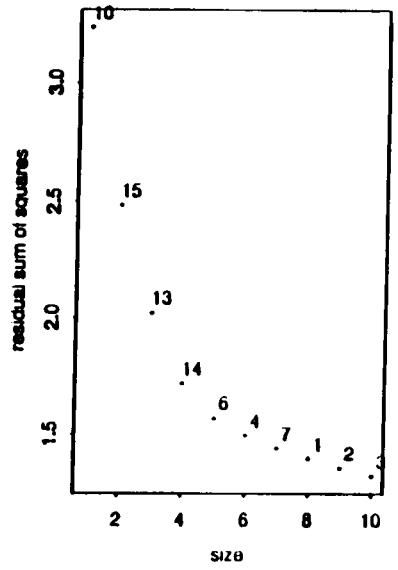
Frequency Distribution



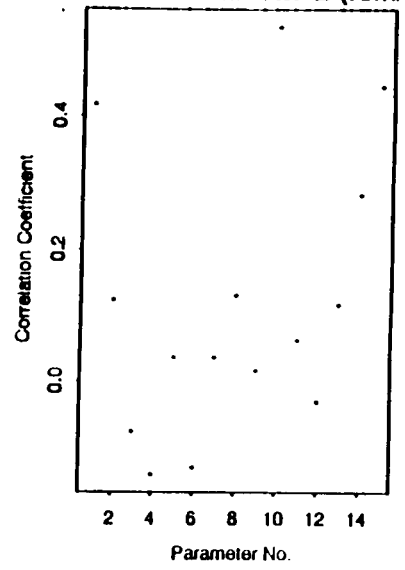
Cumulative Frequency



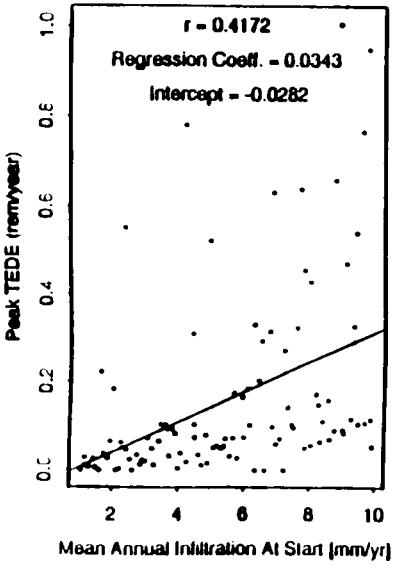
Stepwise Reduction in Error



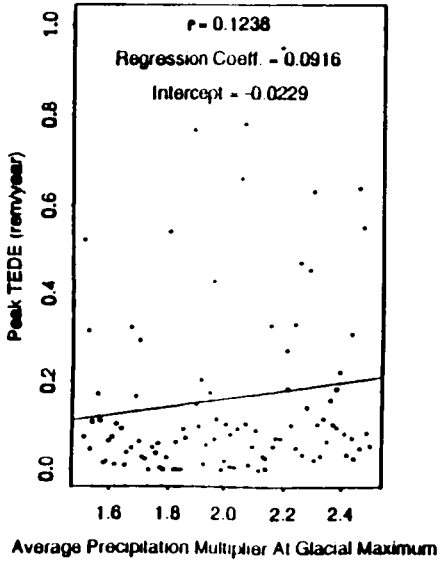
Correlation Coefficients
Parameter ~ Peak TEDE (rem/year)



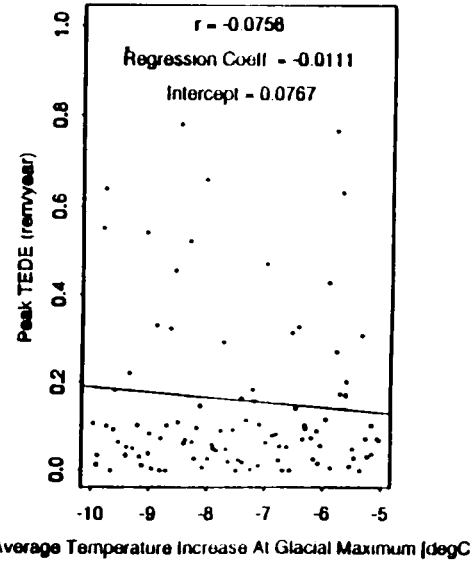
Parameter No. 1



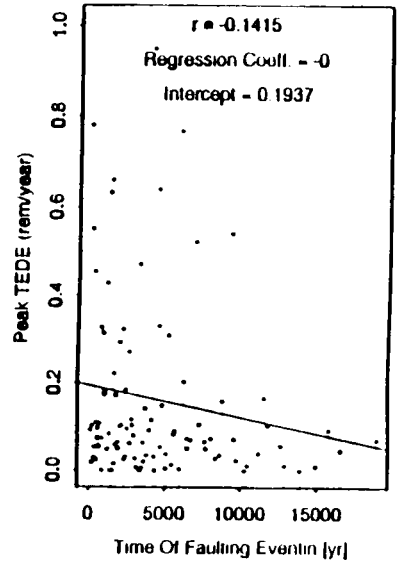
Parameter No. 2



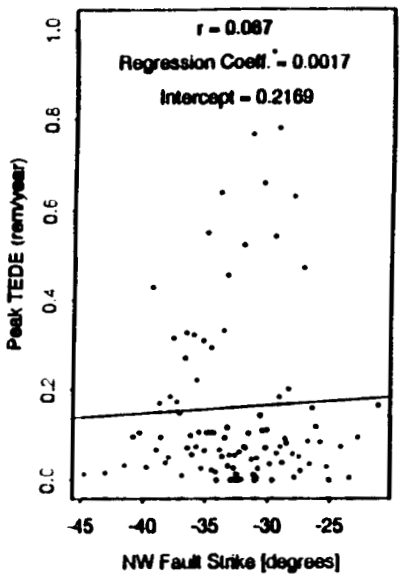
Parameter No. 3



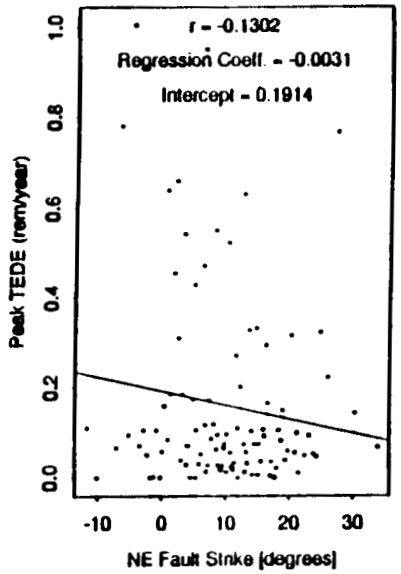
Parameter No. 4



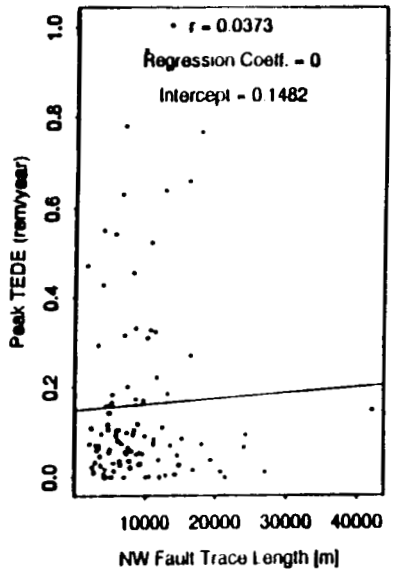
Parameter No. 5



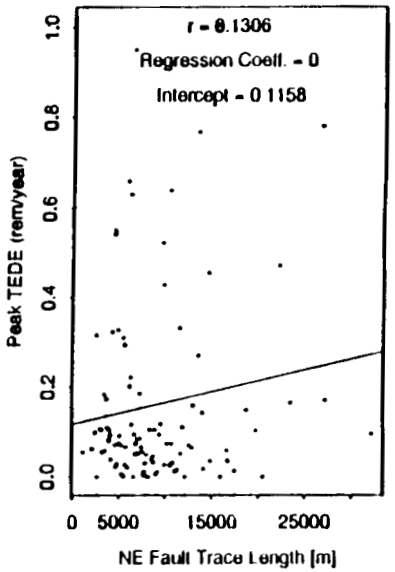
Parameter No. 6



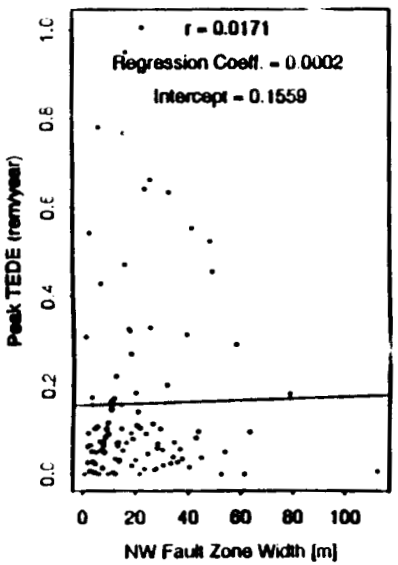
Parameter No. 7



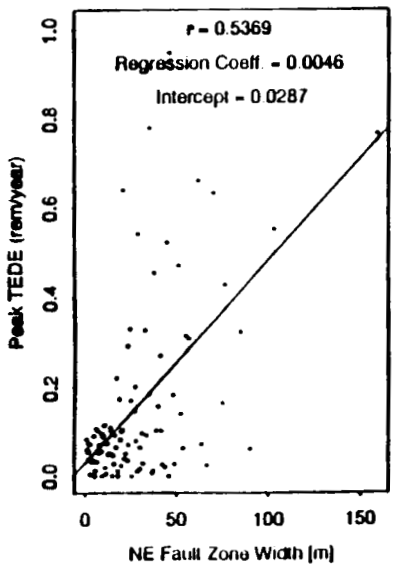
Parameter No. 8



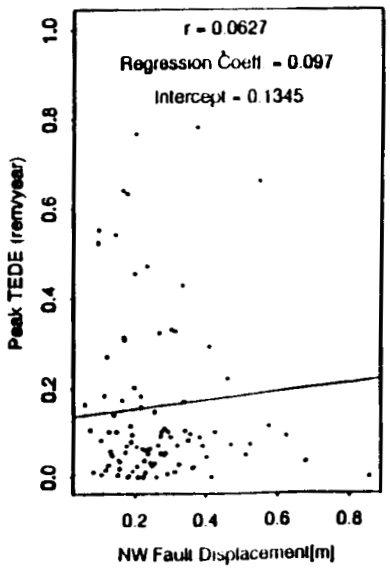
Parameter No. 9



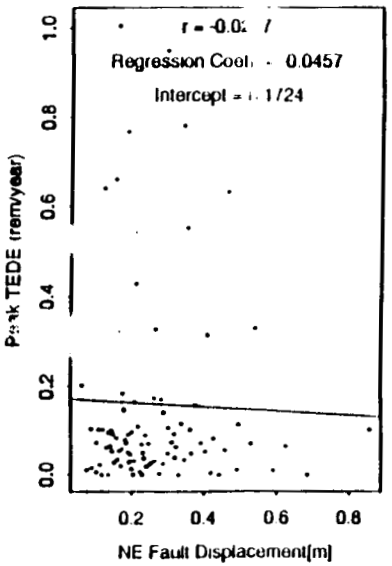
Parameter No. 10



Parameter No. 11

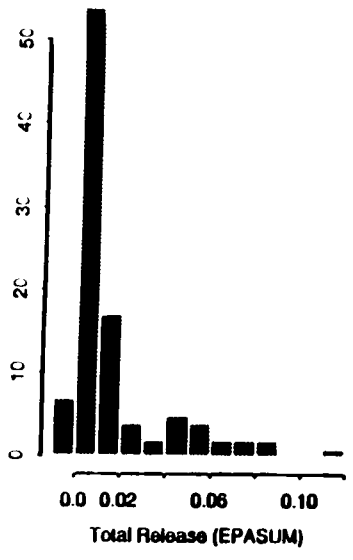


Parameter No. 12

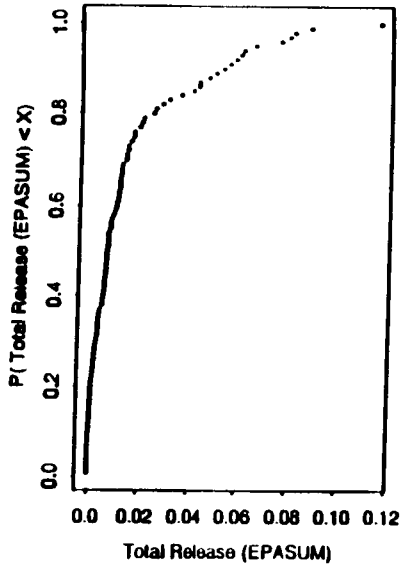


5 km Scenario
Summary Plots for Total Release (EPASUM)

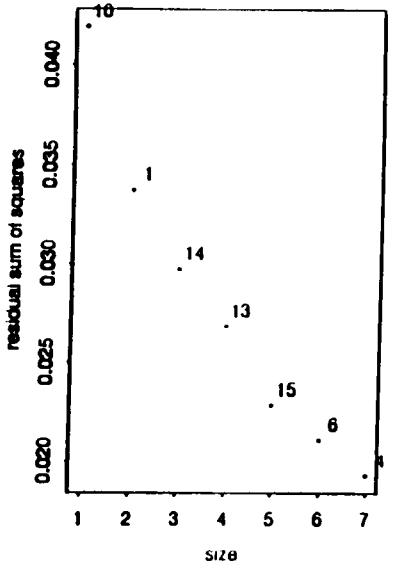
Frequency Distribution



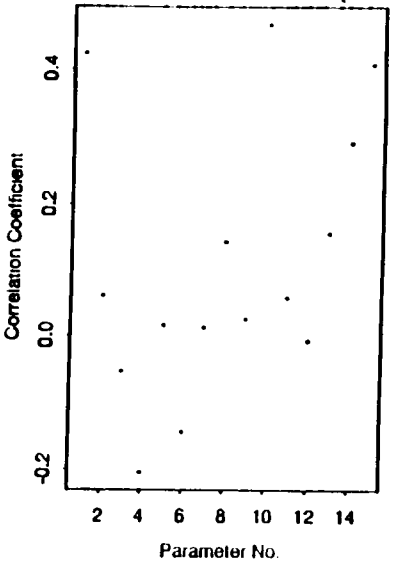
Cumulative Frequency



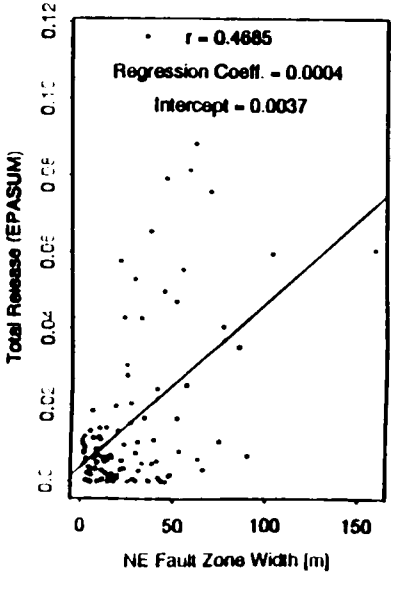
Stepwise Reduction in Error



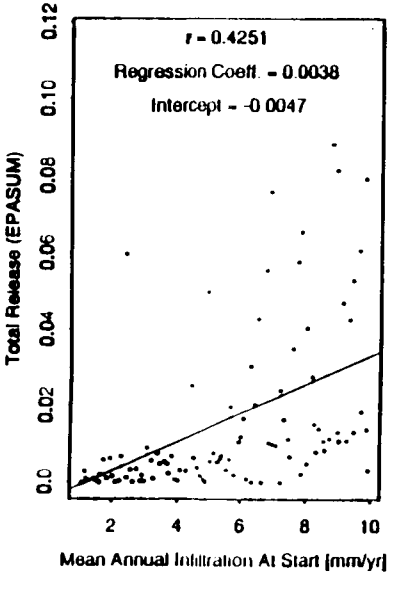
Correlation Coefficients
Parameter ~ Total Release (EPASUM)



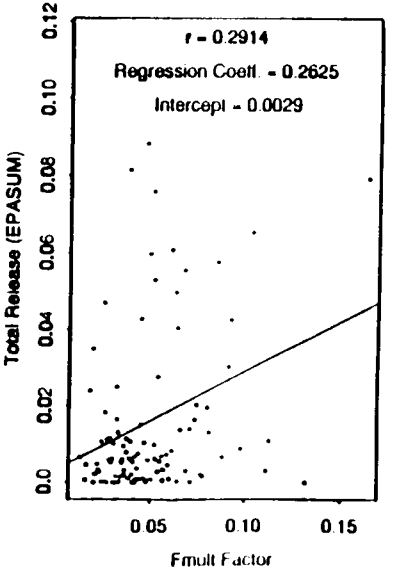
Parameter No. 10



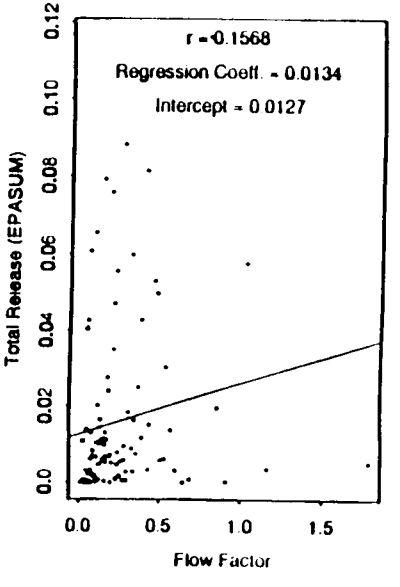
Parameter No. 1



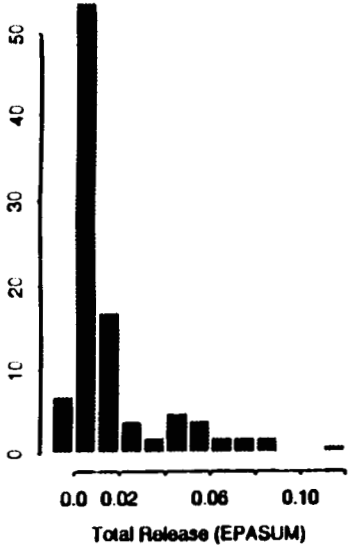
Parameter No. 14

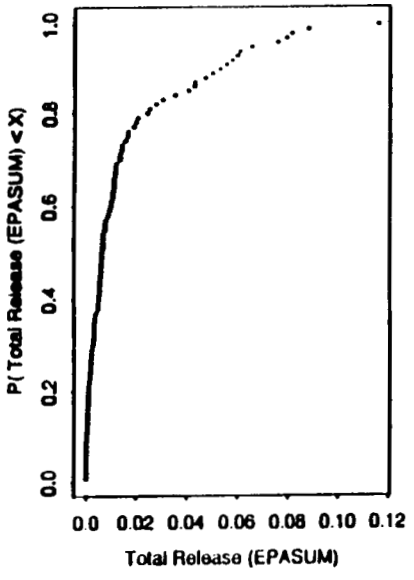


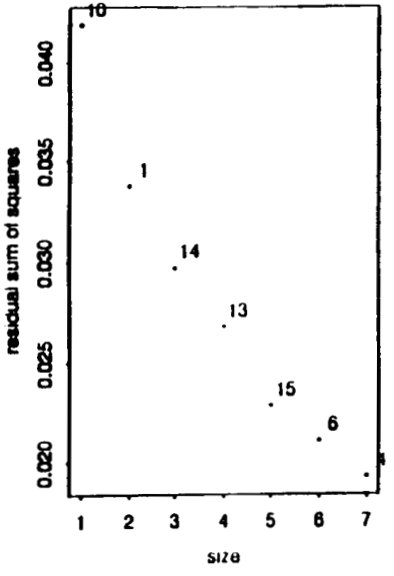
Parameter No. 13

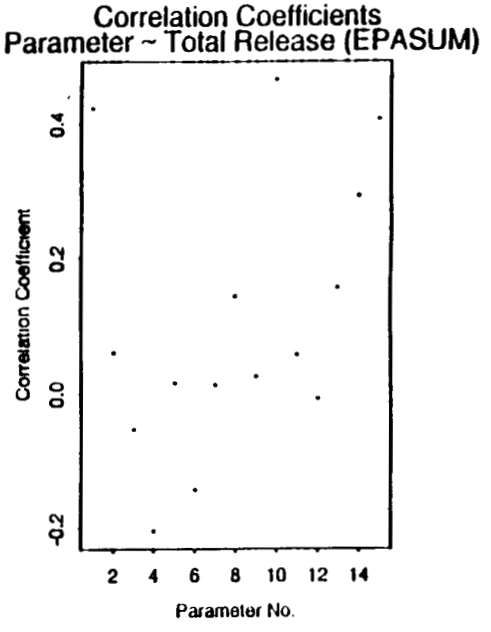


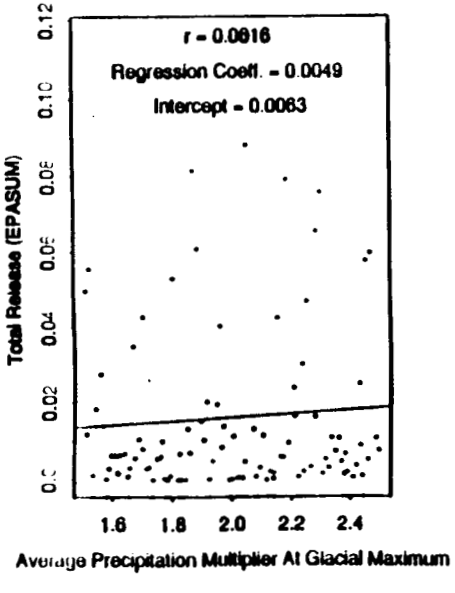
5 km Scenario
Summary Plots for Total Release (EPASUM)

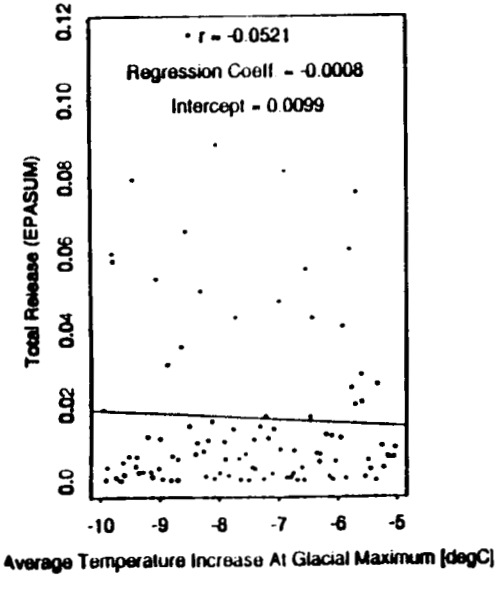


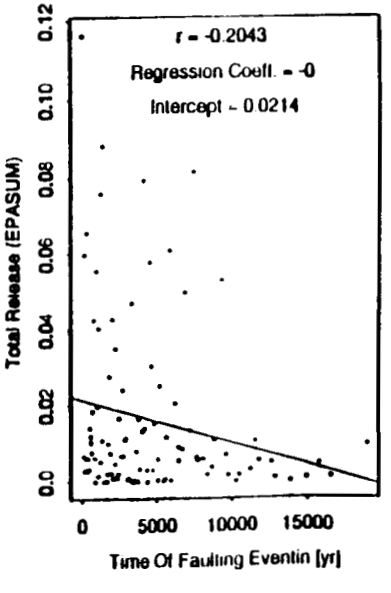


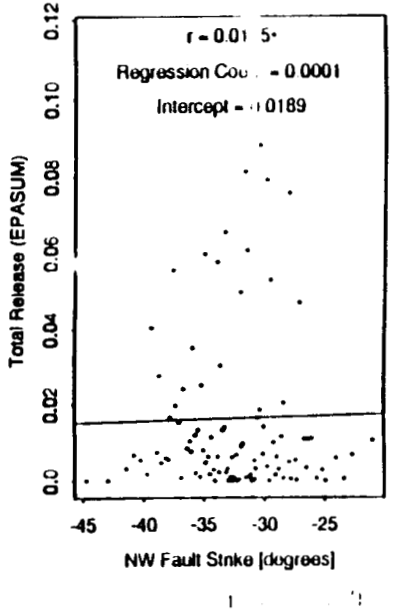




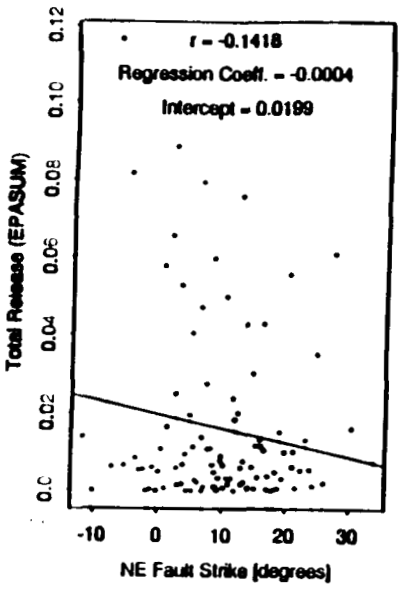




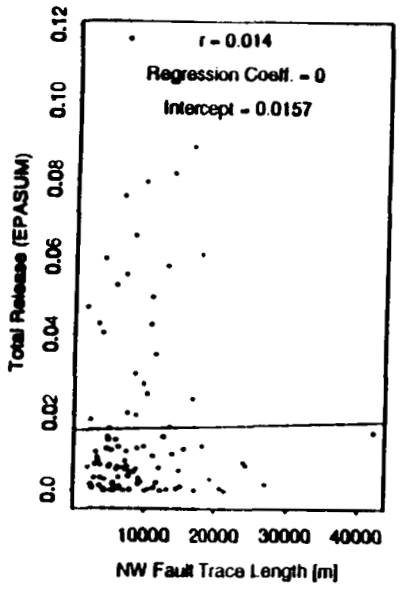




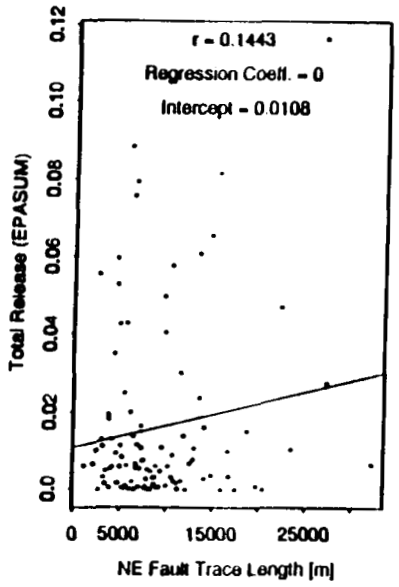
Parameter No. 6



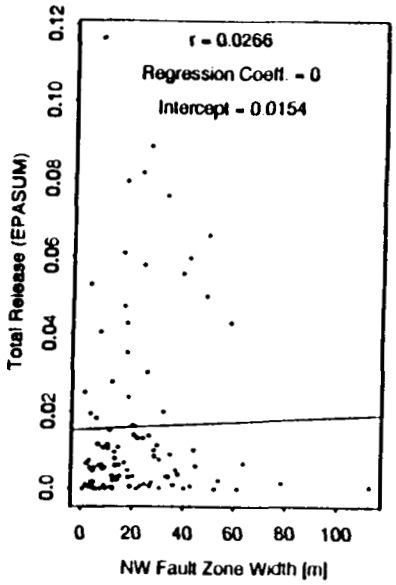
Parameter No. 7



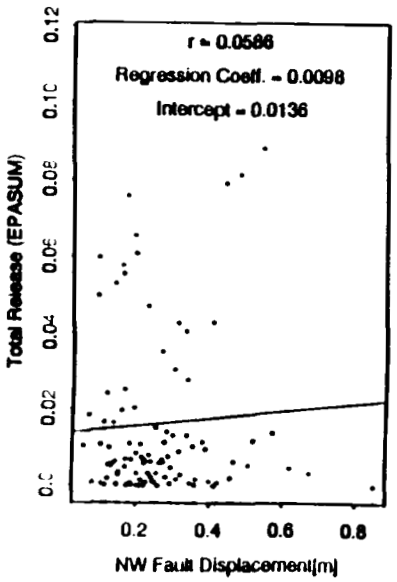
Parameter No. 8



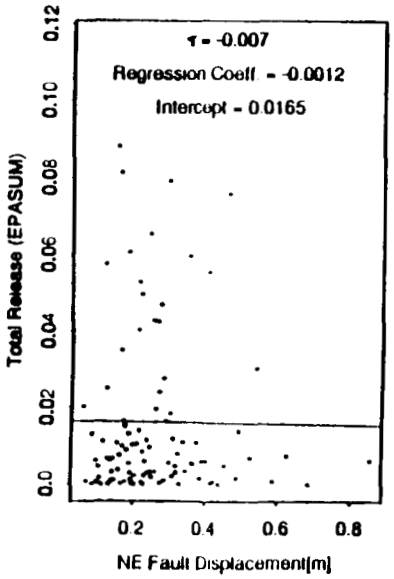
Parameter No. 9



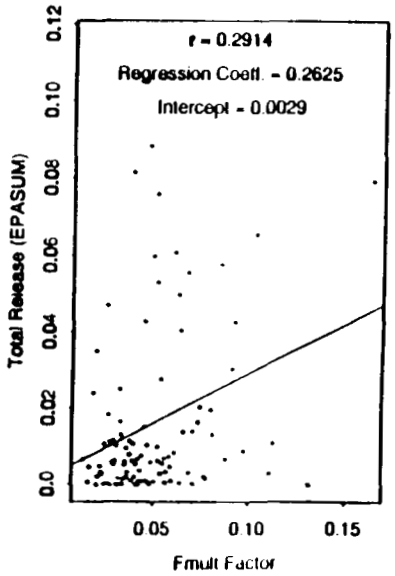
Parameter No. 11



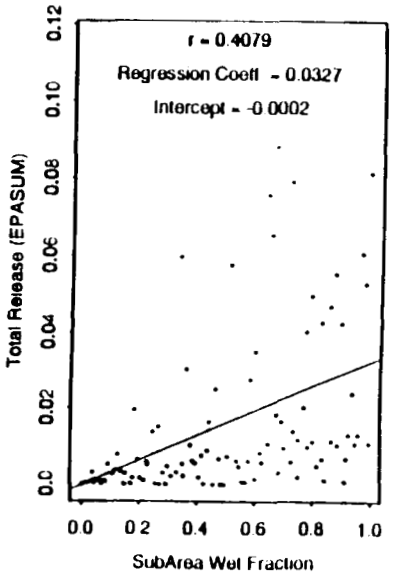
Parameter No. 12



Parameter No. 14



Parameter No. 15



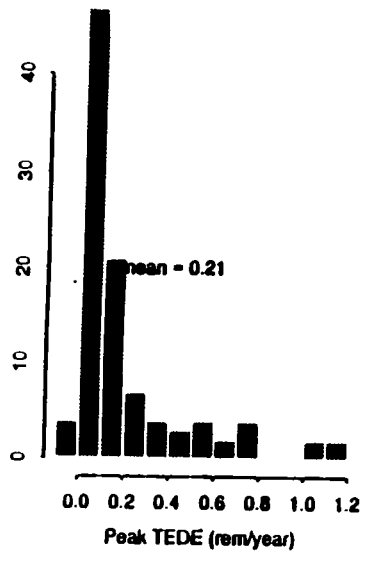
53/94

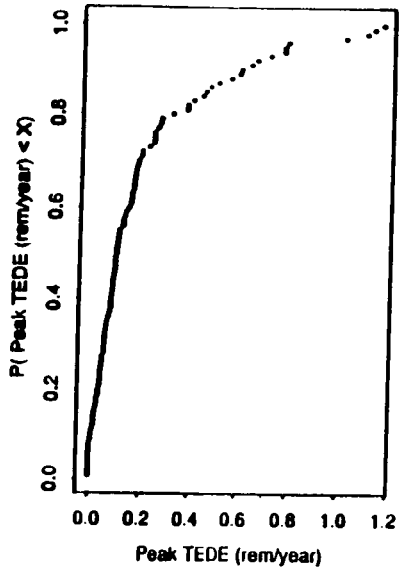
APPENDIX F

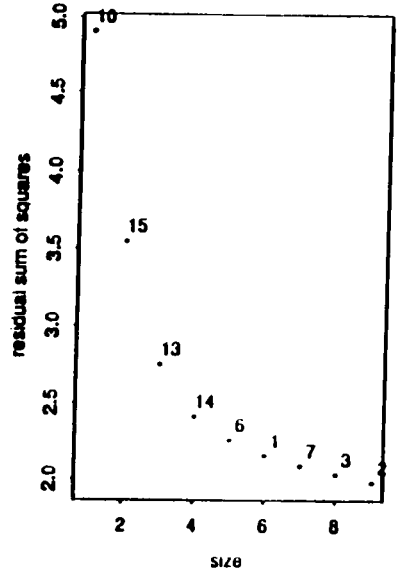
Run: FLTO_Run5

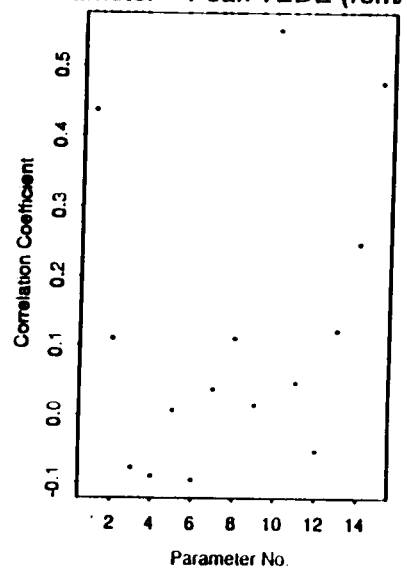
Distance to Critical Group = 5 km
Recurrence Interval = 500 yr
Only FAULTO, Uniform Corrosion, Backfill

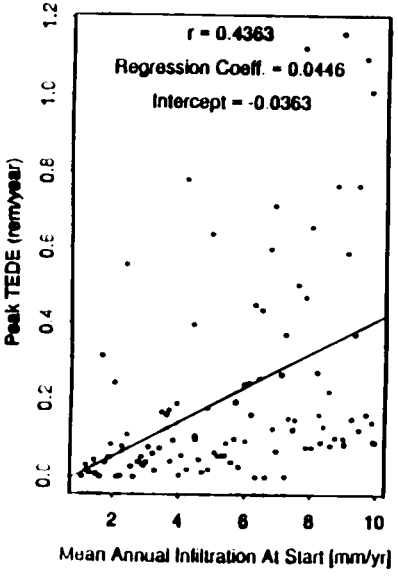
5 km Scenario
Summary Plots for Peak TEDE (rem/year)

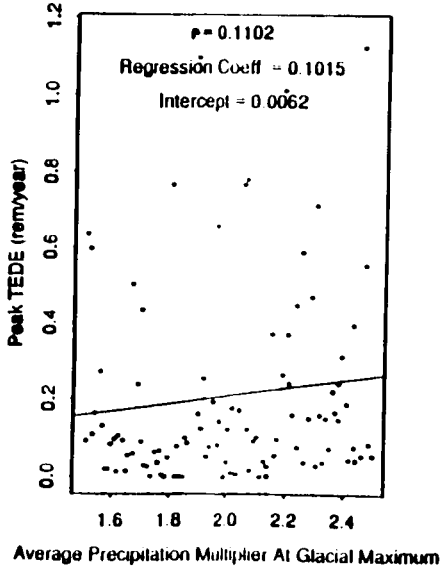


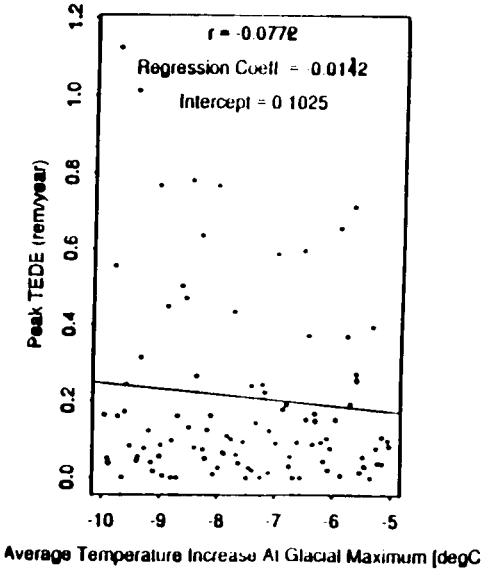


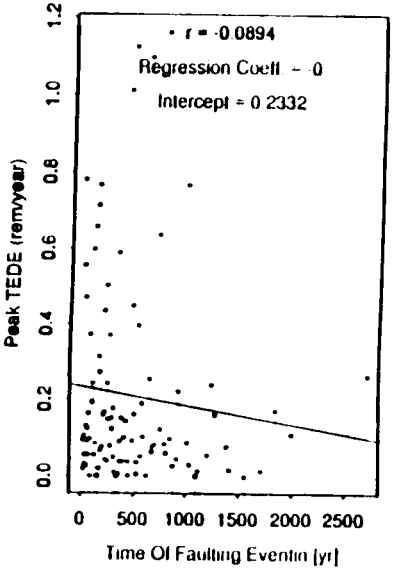




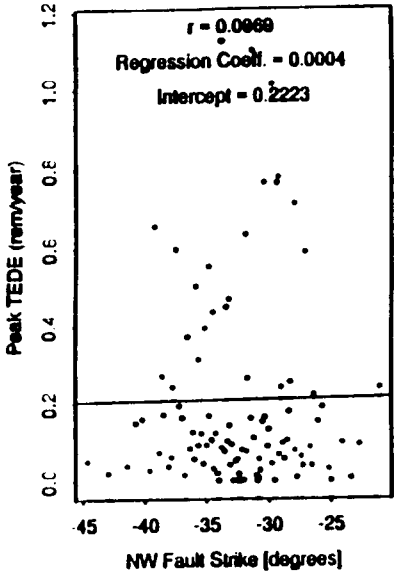




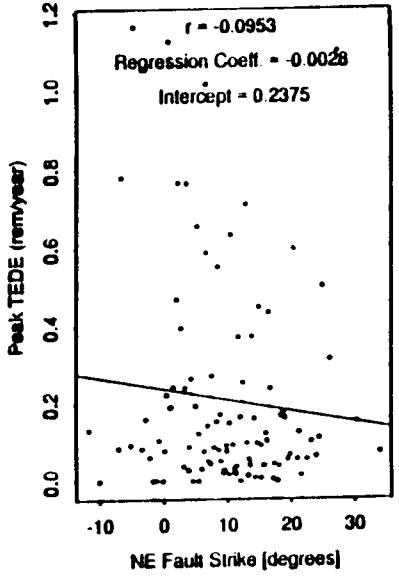




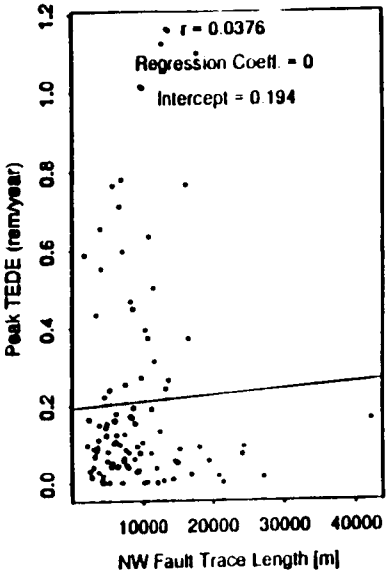
Parameter No. 5



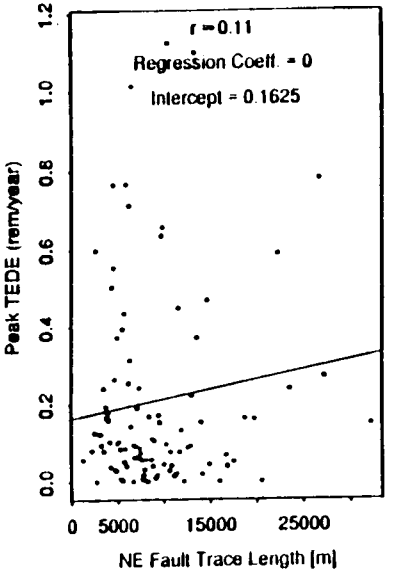
Parameter No. 6



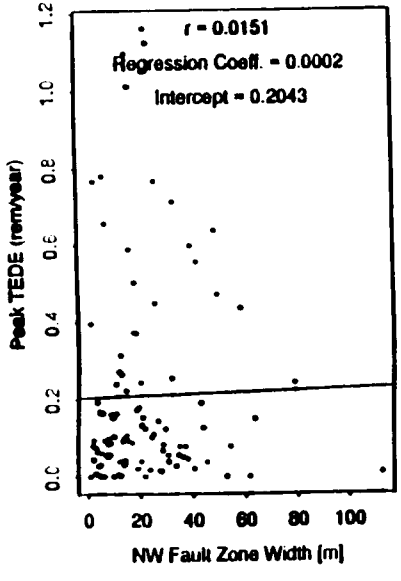
Parameter No. 7



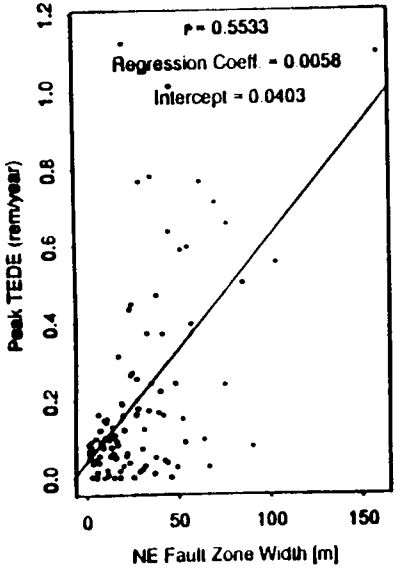
Parameter No. 8



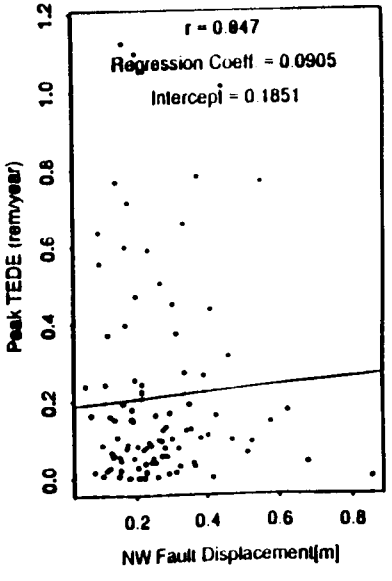
Parameter No. 9



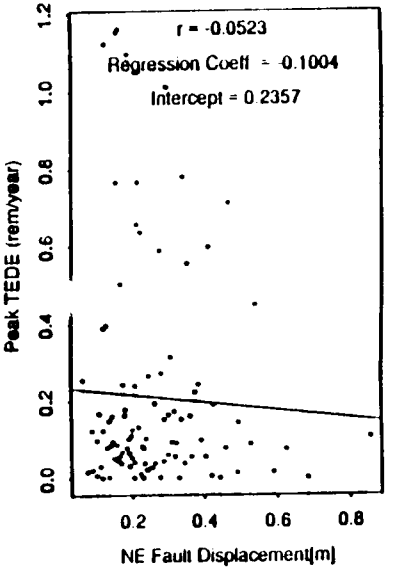
Parameter No. 10



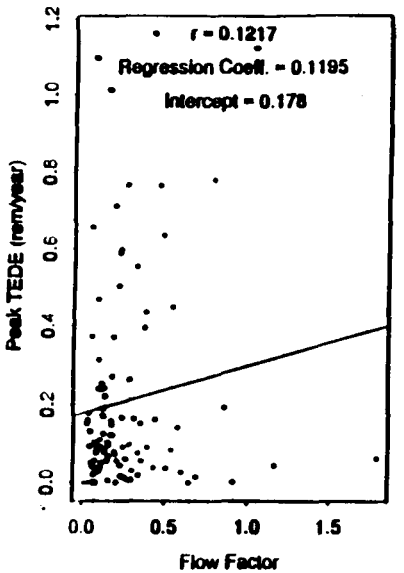
Parameter No. 11



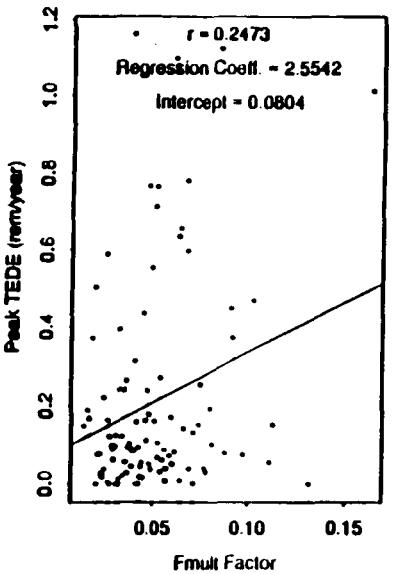
Parameter No. 12



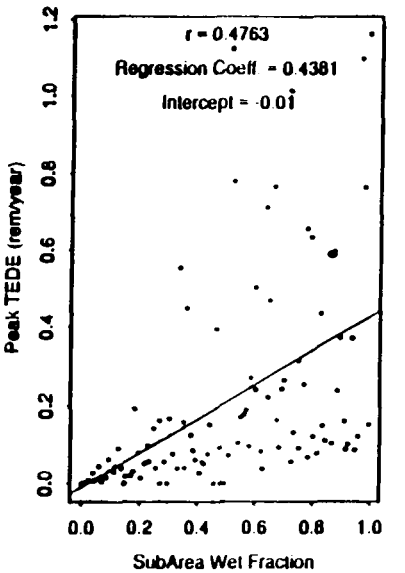
Parameter No. 13



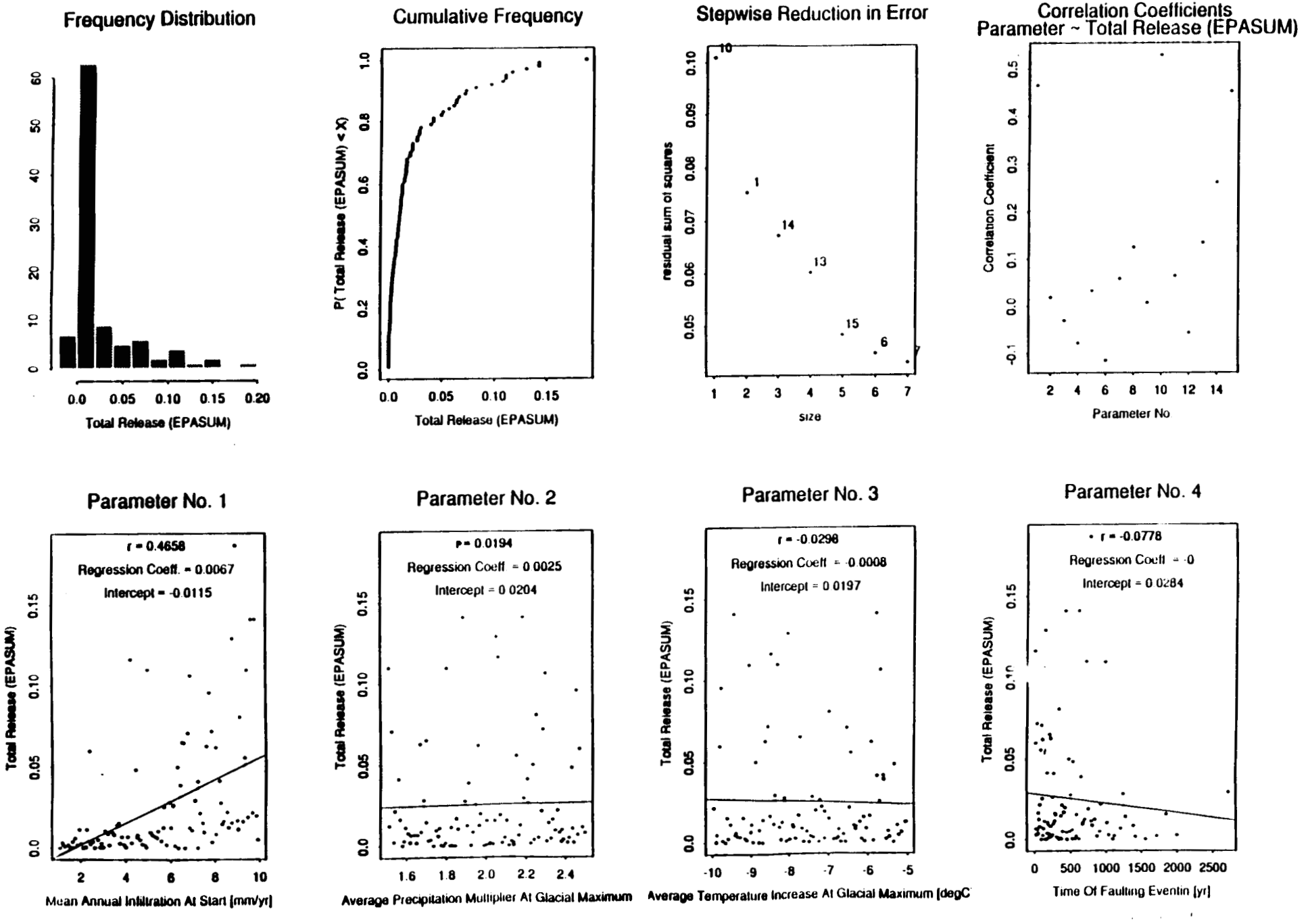
Parameter No. 14



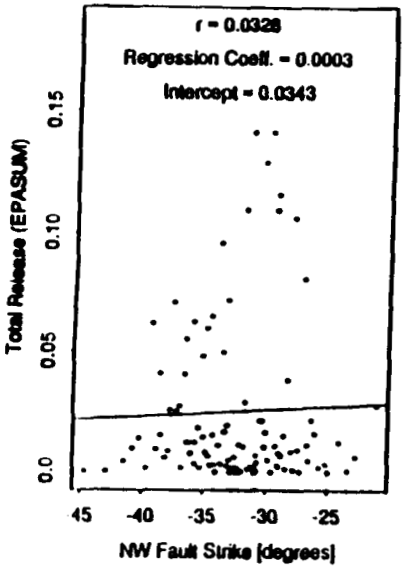
Parameter No. 15



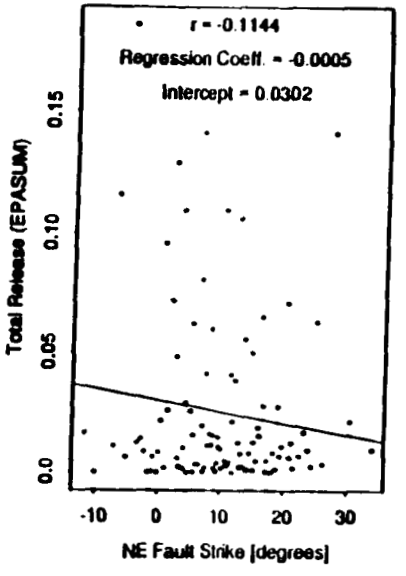
5 km Scenario
Summary Plots for Total Release (EPASUM)



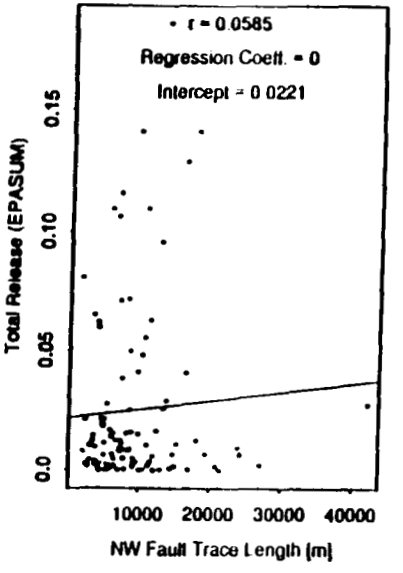
Parameter No. 5



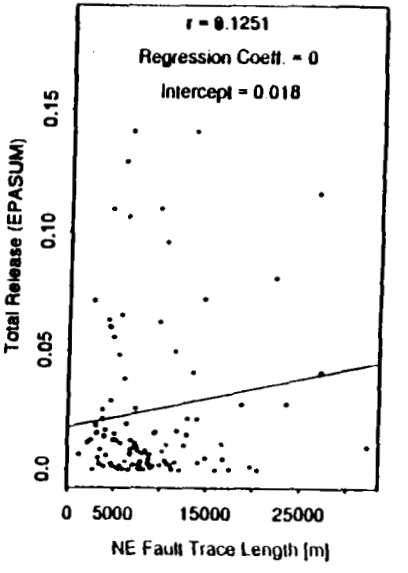
Parameter No. 6



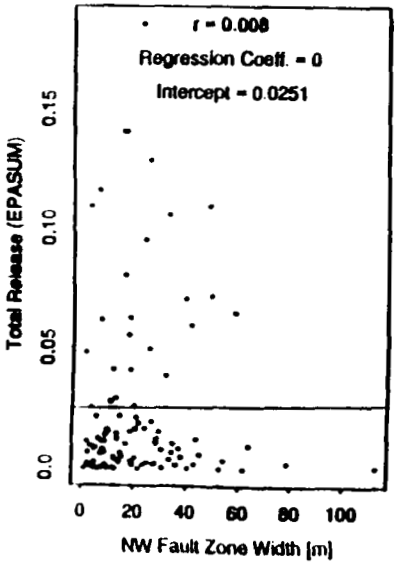
Parameter No. 7



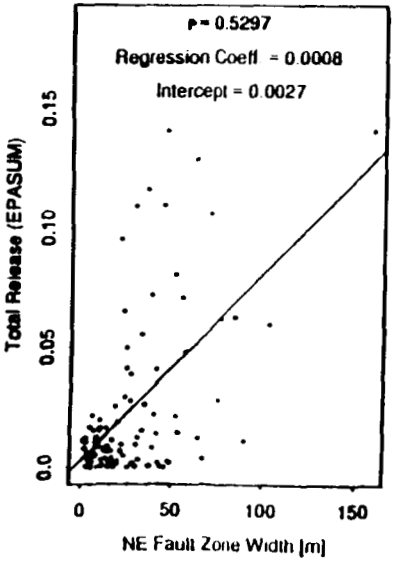
Parameter No. 8



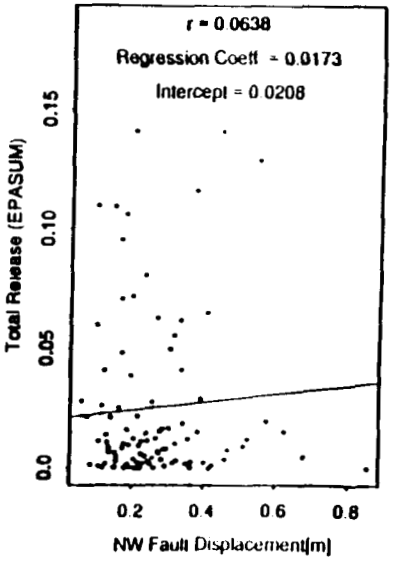
Parameter No. 9



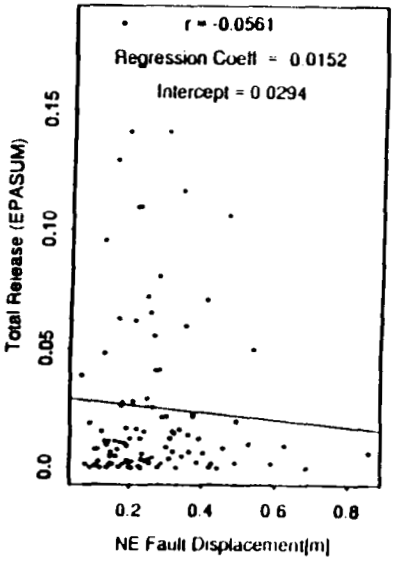
Parameter No. 10



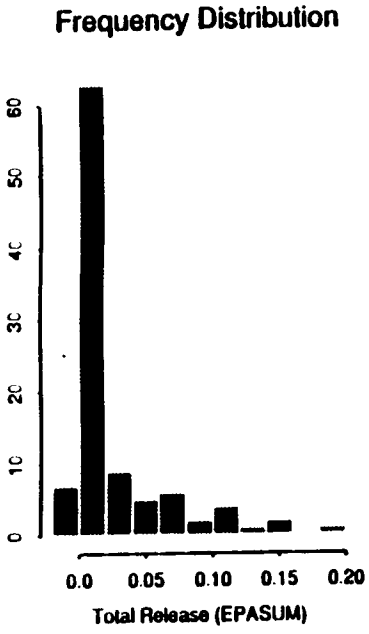
Parameter No. 11

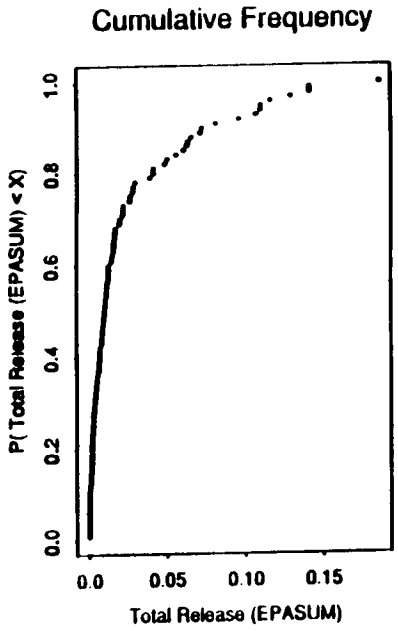


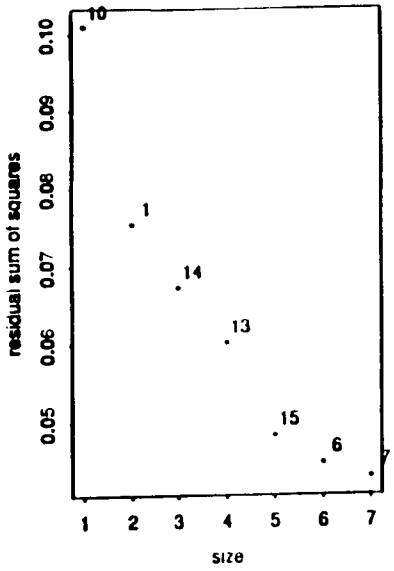
Parameter No. 12

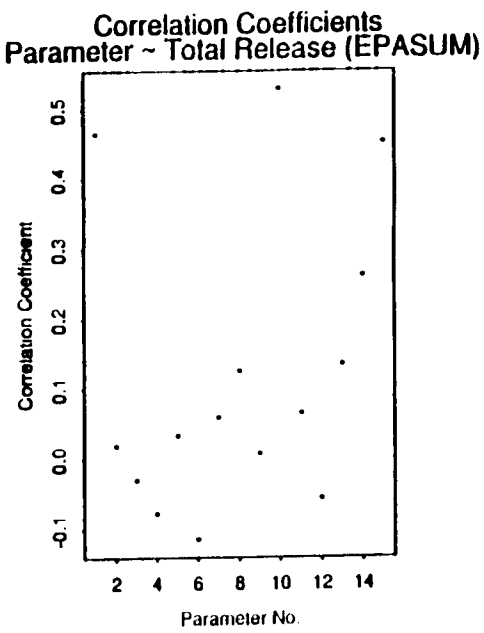


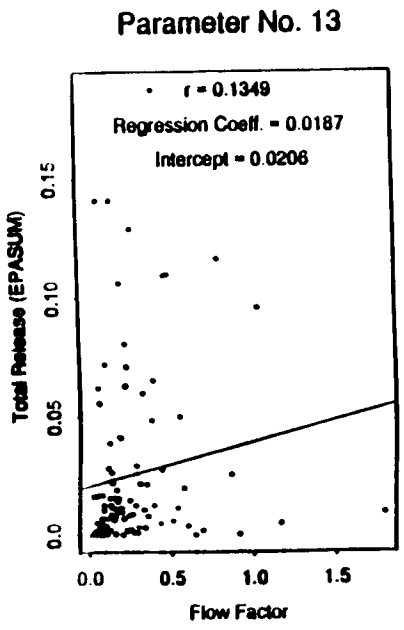
5 km Scenario
Summary Plots for Total Release (EPASUM)

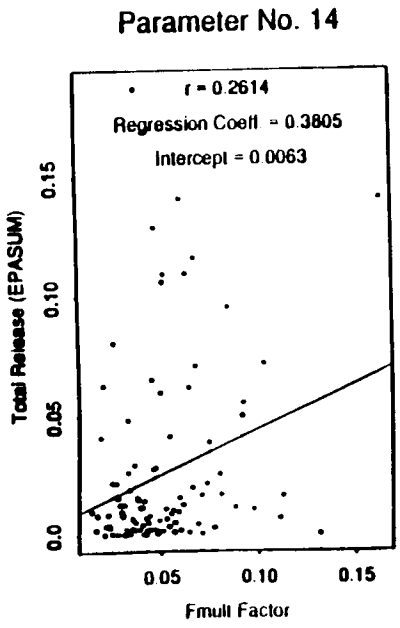


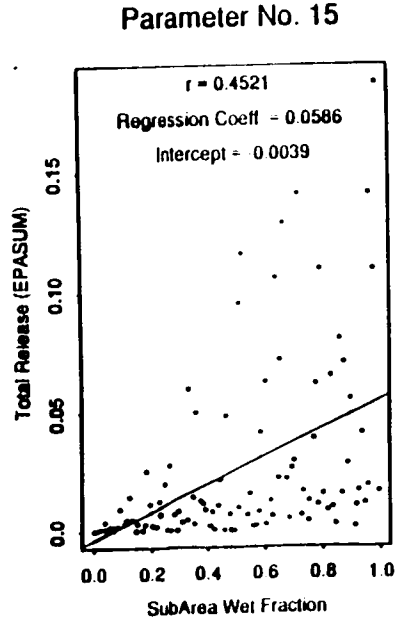




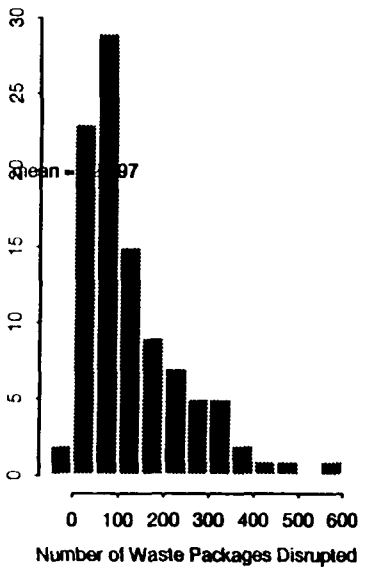


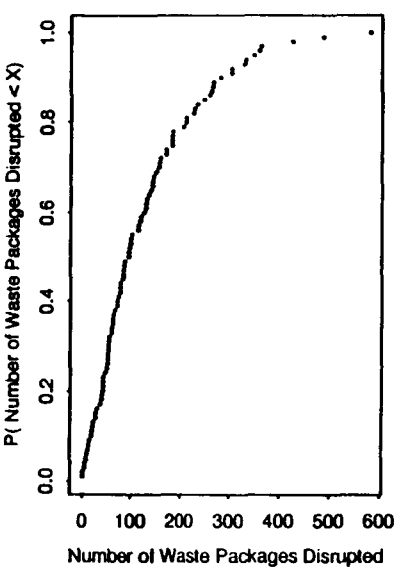


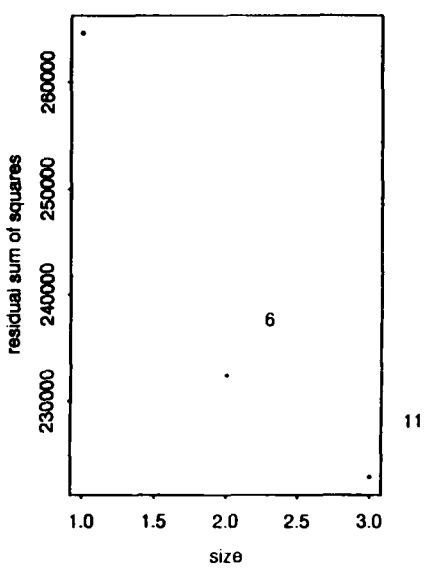


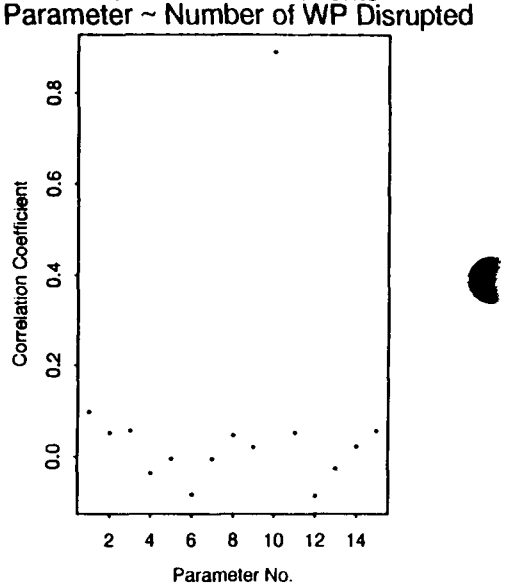


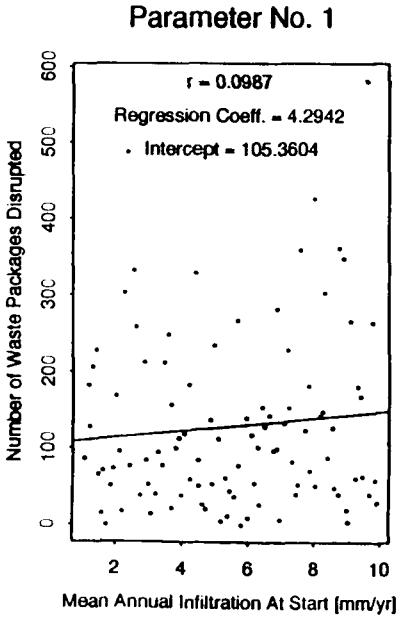
5 km Scenario
Summary Plots for Number of Waste Packages Disrupted

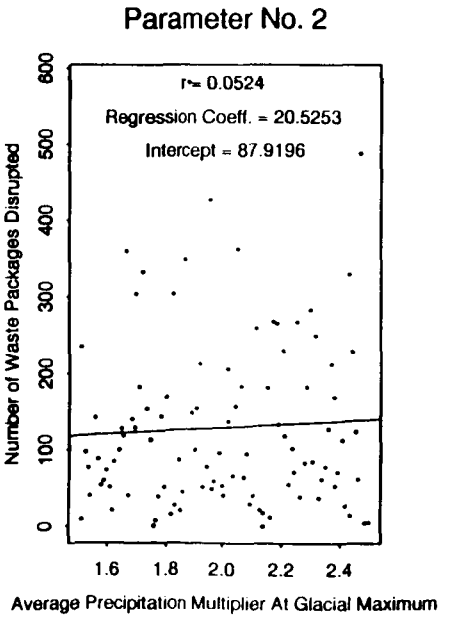


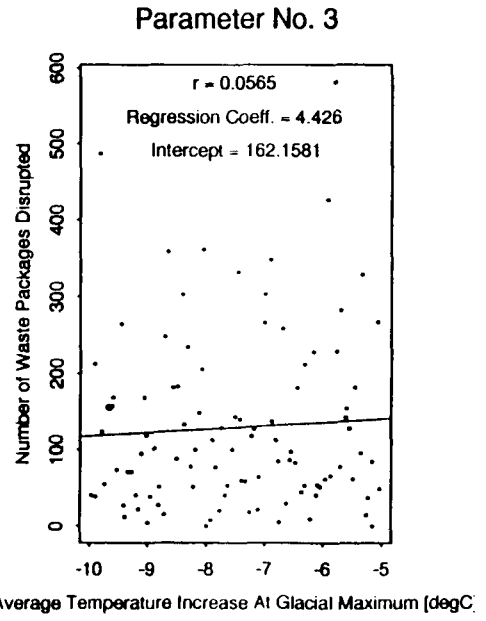


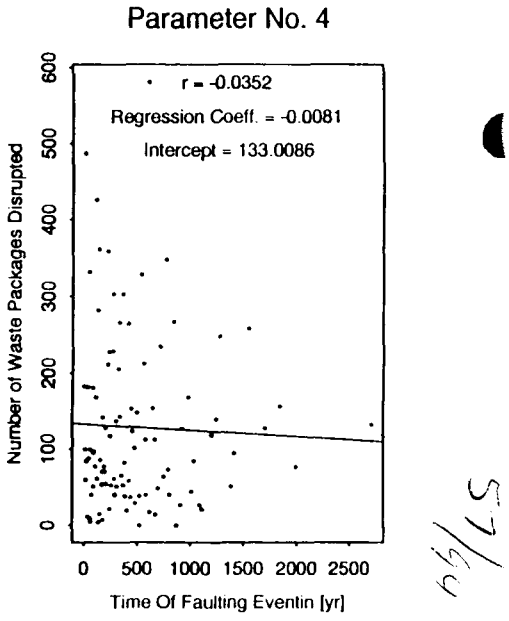




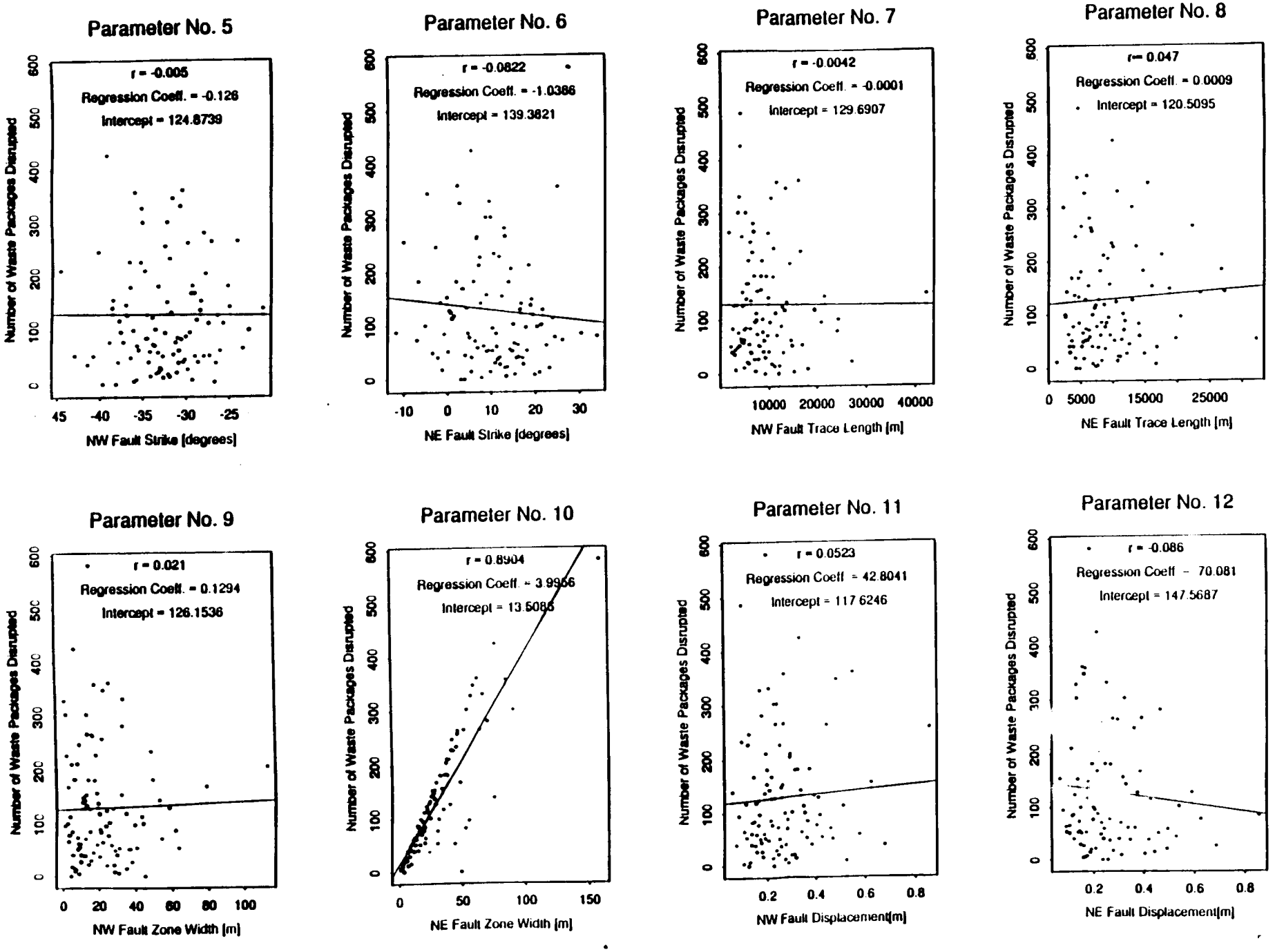




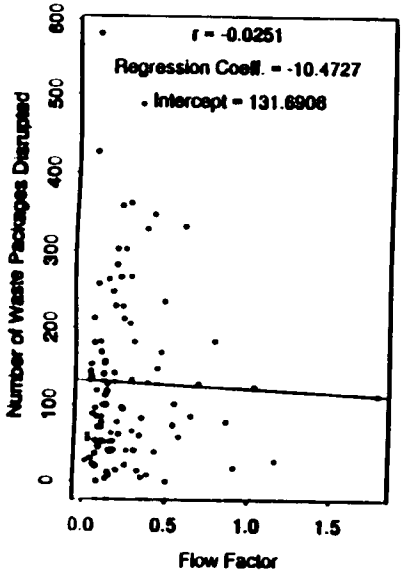




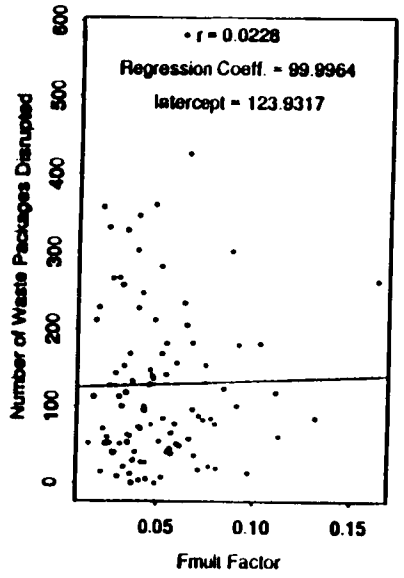
57/99


Parameter No. 5
r = -0.005
Regression Coeff. = -0.126
Intercept = 124.8739
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. = 42.8041
Intercept = 117.6246
Number of Waste Packages Disrupted
NW Fault Displacement[m]
Parameter No. 12
r = -0.086
Regression Coeff. = 70.081
Intercept = 147.5687
Number of Waste Packages Disrupted
NE Fault Displacement[m]

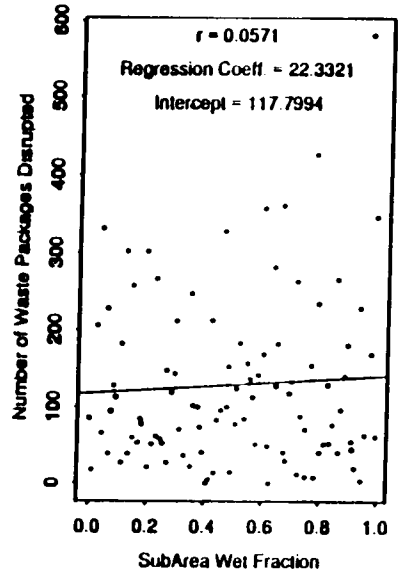
Parameter No. 13



Parameter No. 14



Parameter No. 15



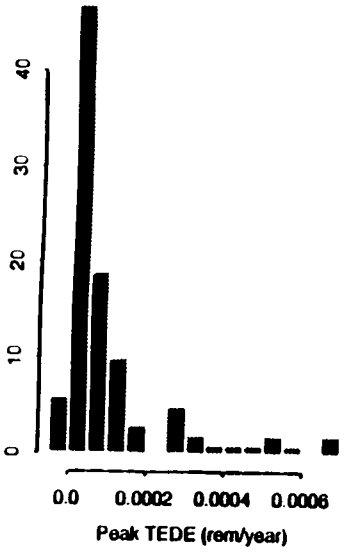
59/94

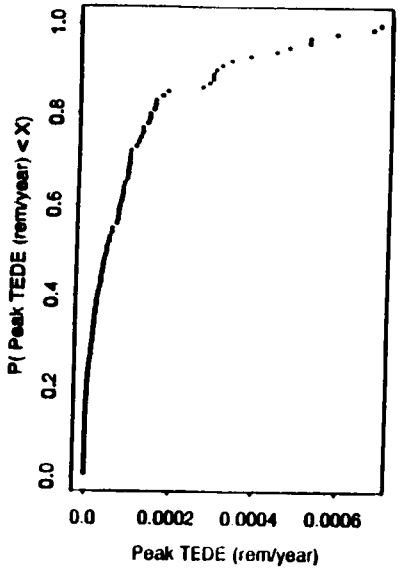
APPENDIX G

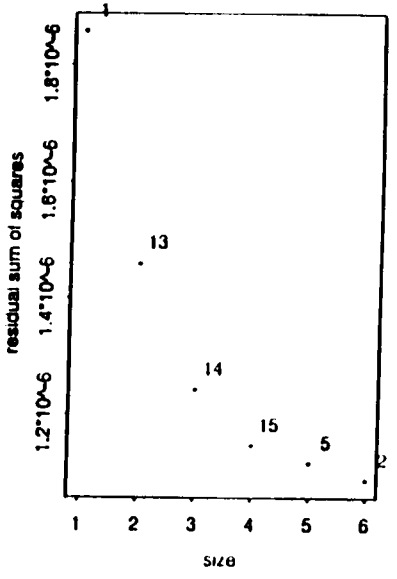
Run: FLTO_Run6

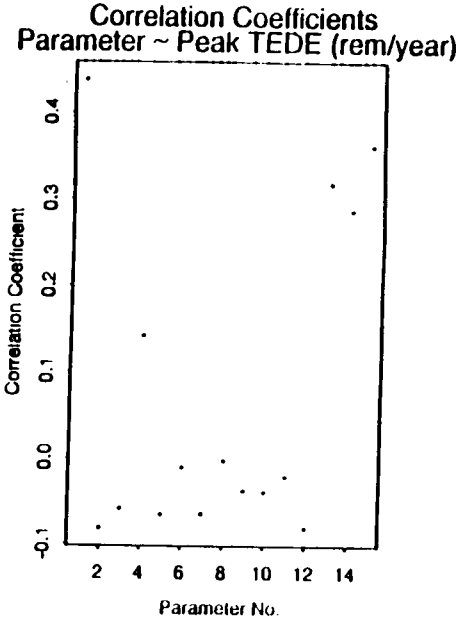
Distance to Critical Group = 20 km
Recurrence Interval = 5,000 yr
Only FAULTO, Localized Corrosion, Backfill

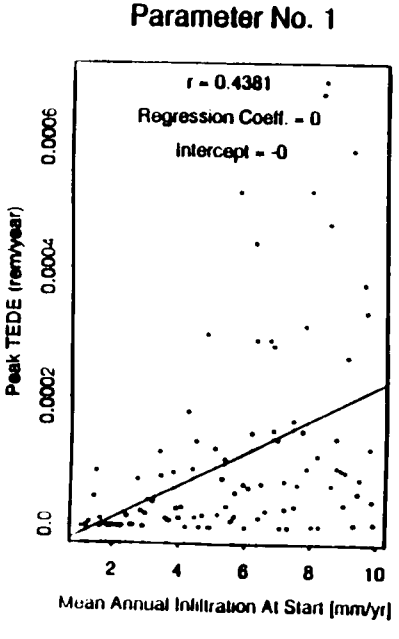
20 km Scenario
Summary Plots for Peak TEDE (rem/year)

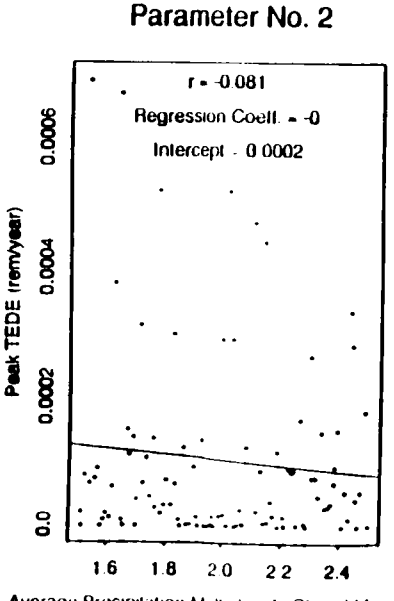


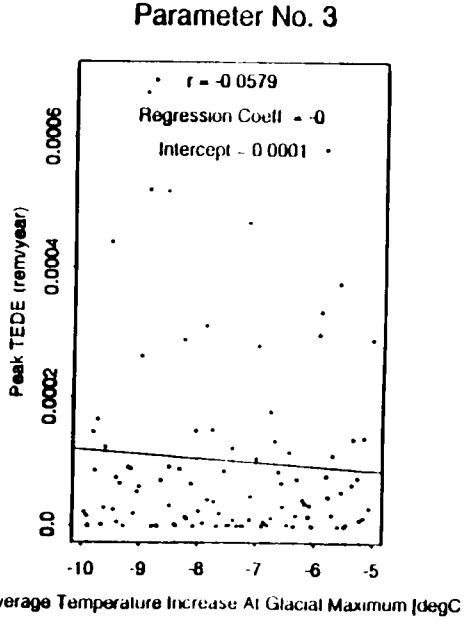


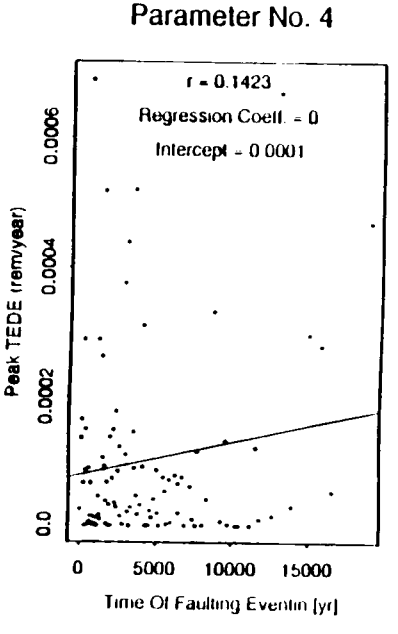




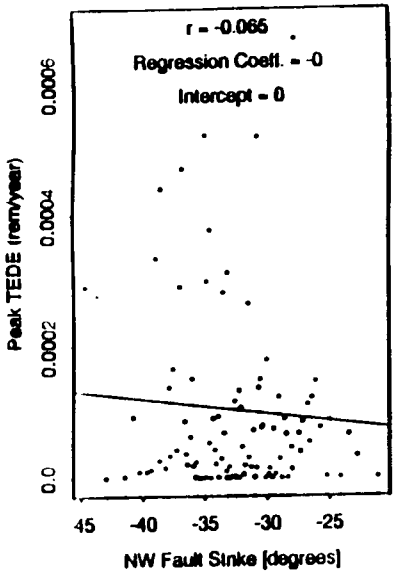




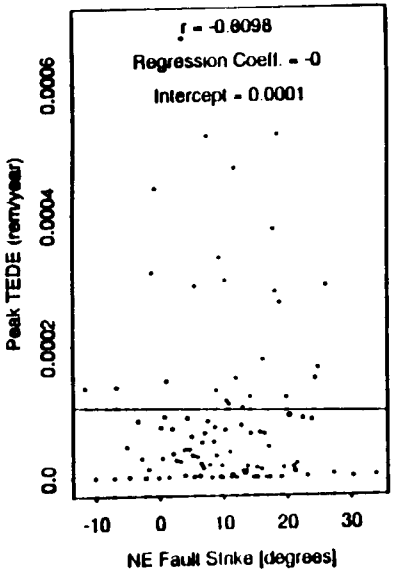




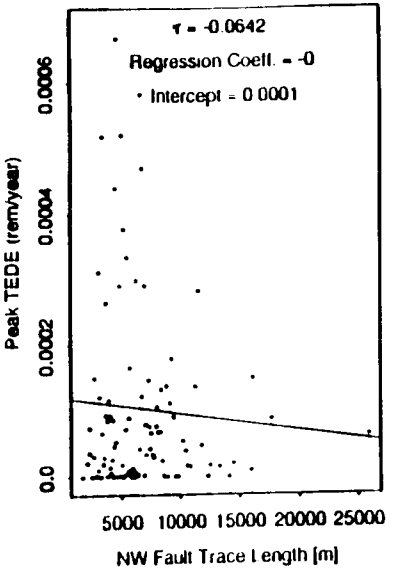
Parameter No. 5



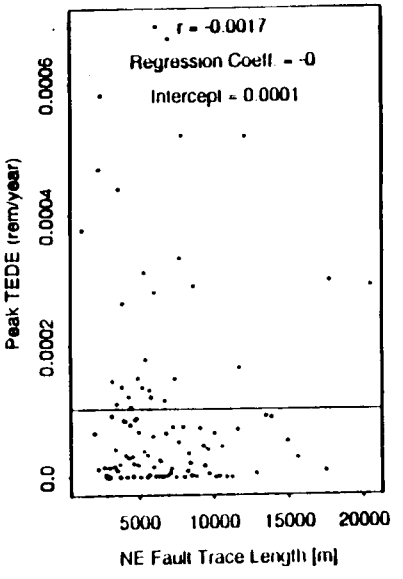
Parameter No. 6



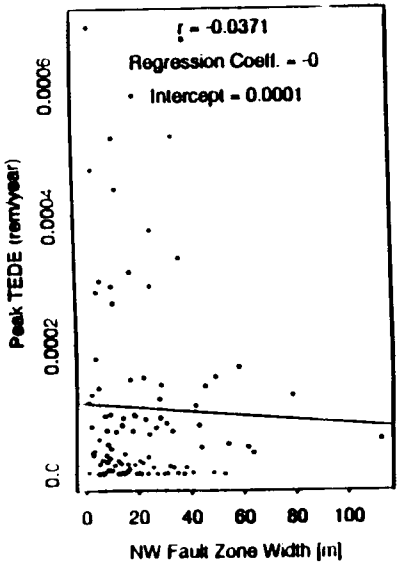
Parameter No. 7



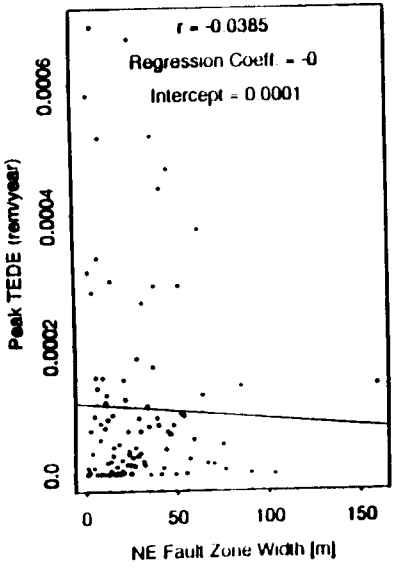
Parameter No. 8



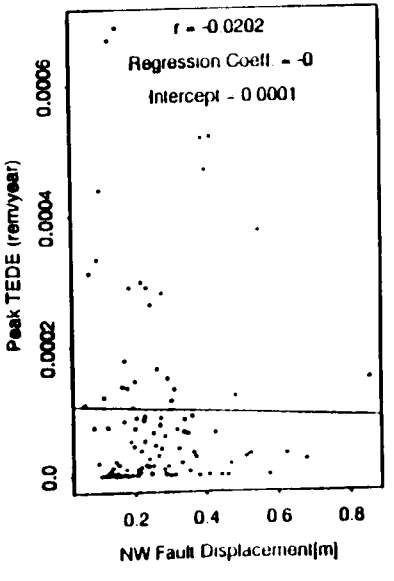
Parameter No. 9



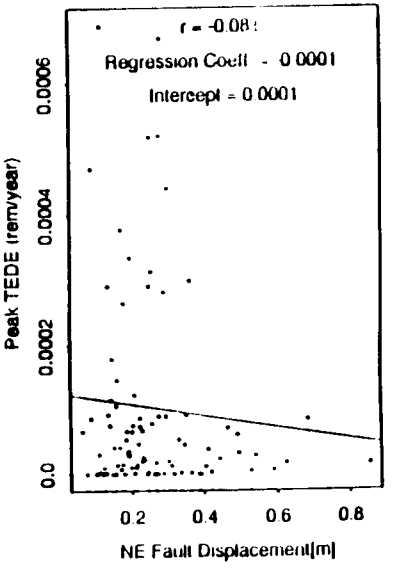
Parameter No. 10



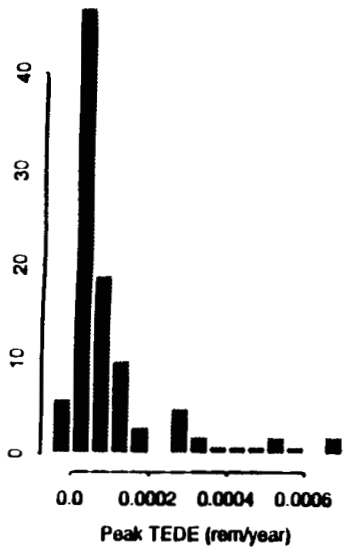
Parameter No. 11

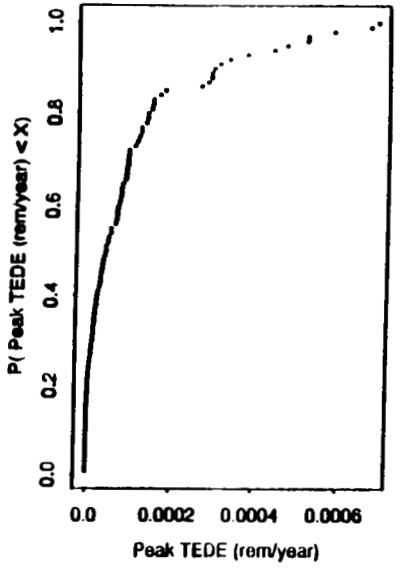


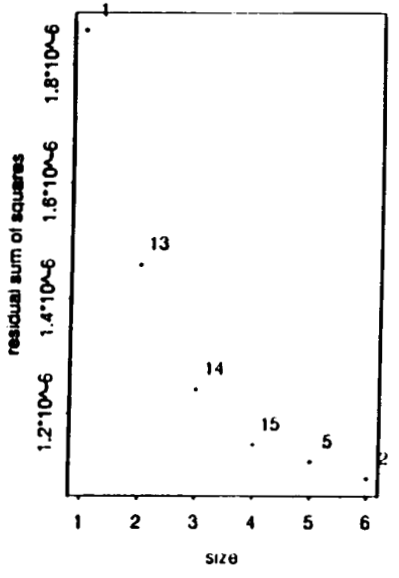
Parameter No. 12

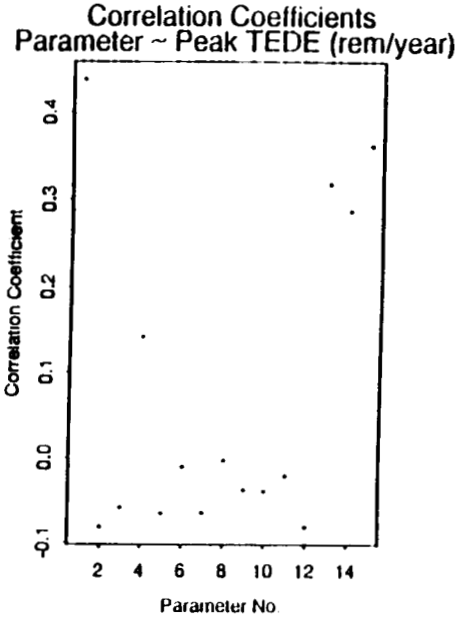


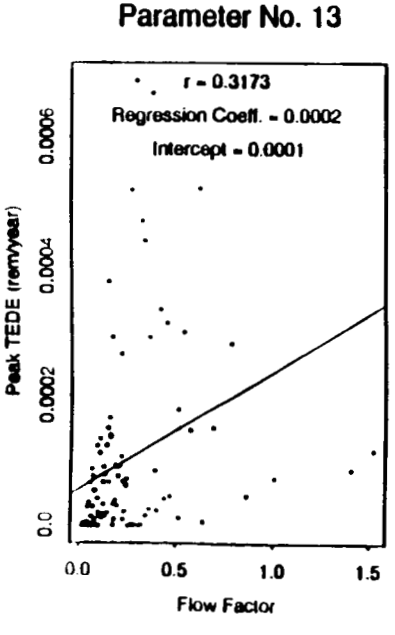
20 km Scenario
Summary Plots for Peak TEDE (rem/year)

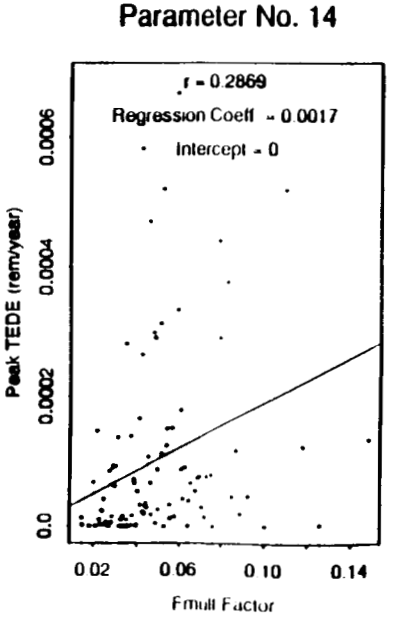


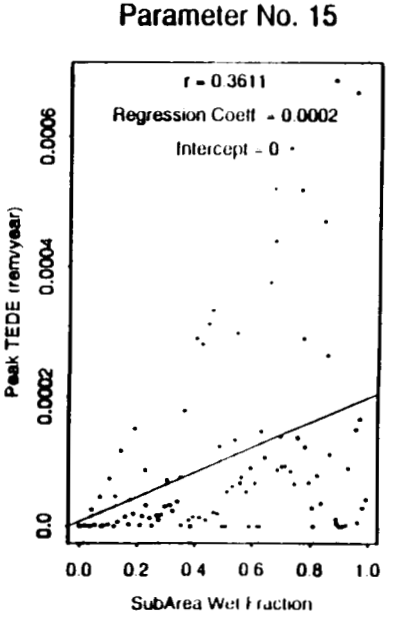




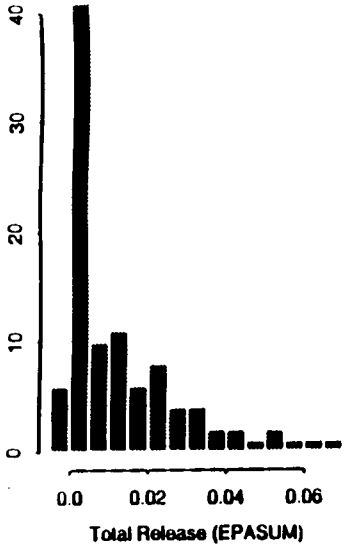


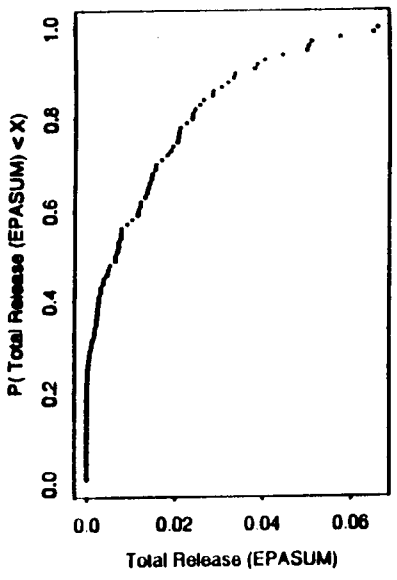


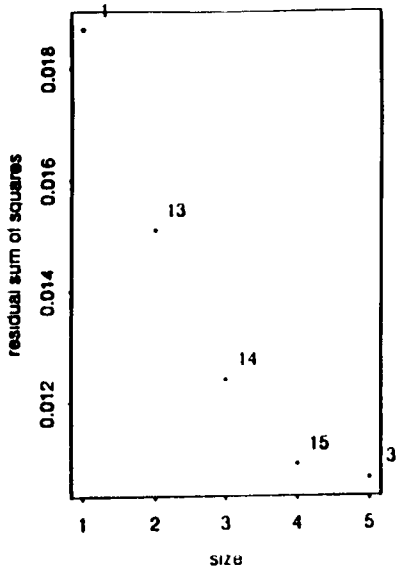


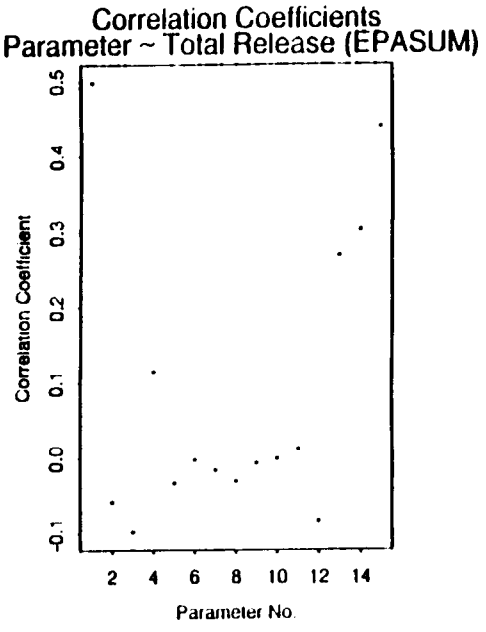


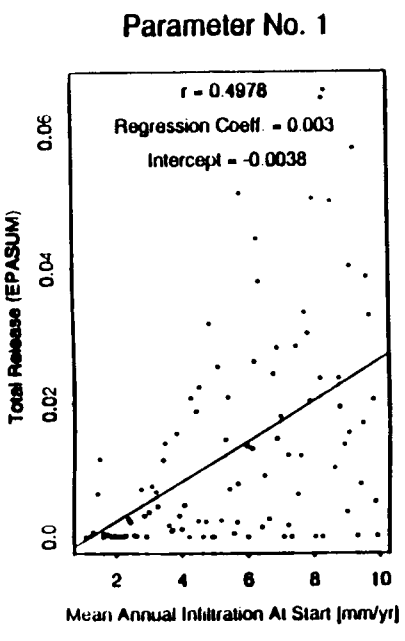
20 km Scenario
Summary Plots for Total Release (EPASUM)

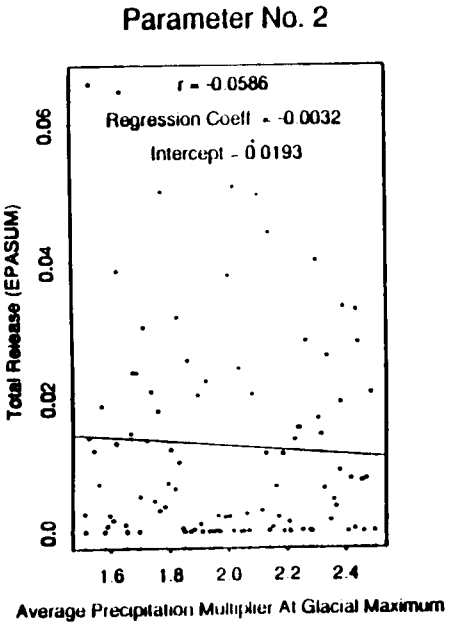


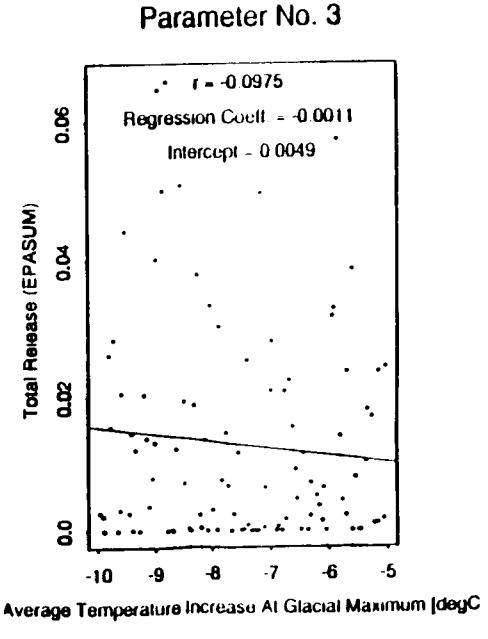


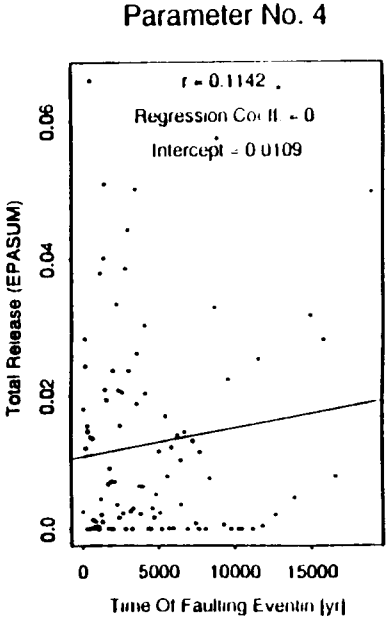




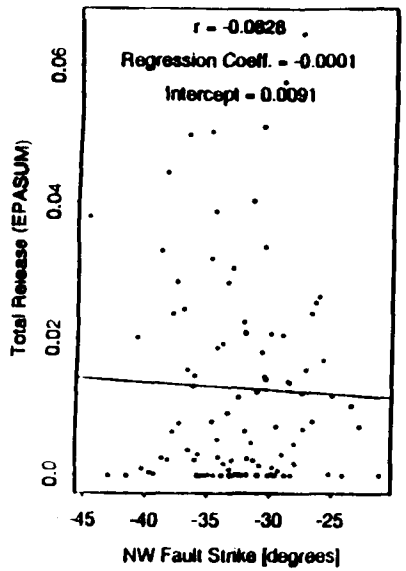




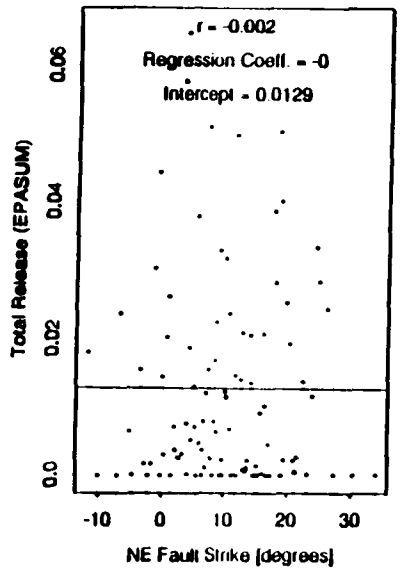




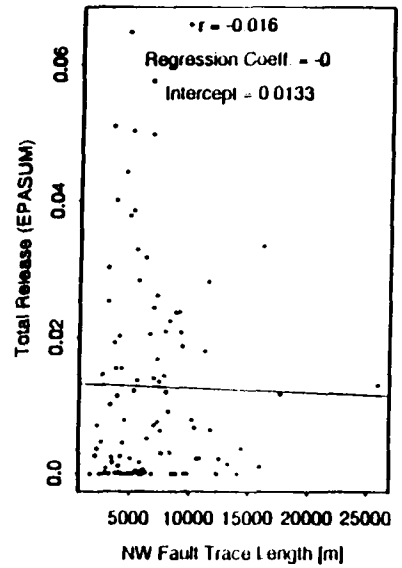
Parameter No. 5



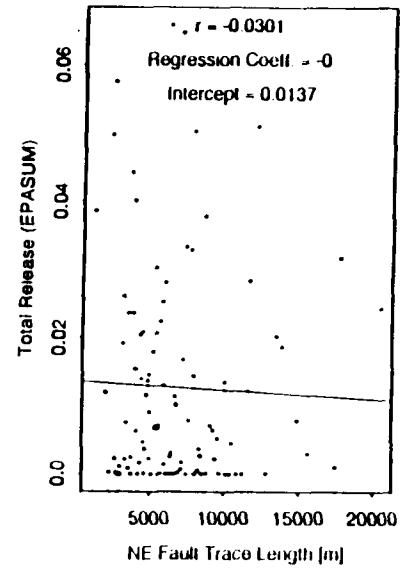
Parameter No. 6



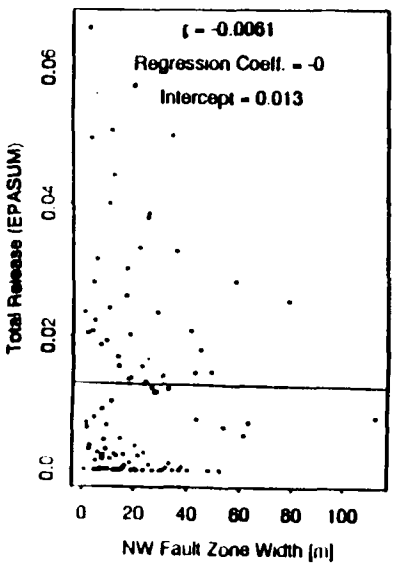
Parameter No. 7



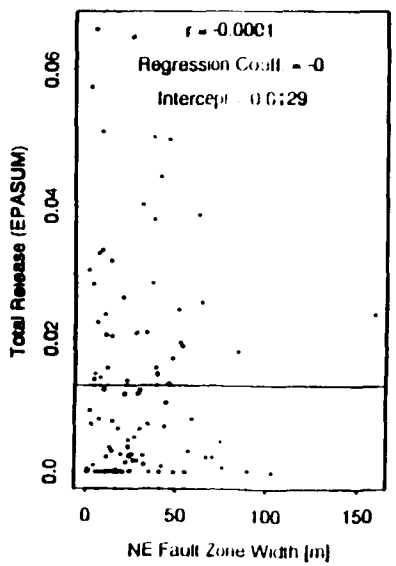
Parameter No. 8



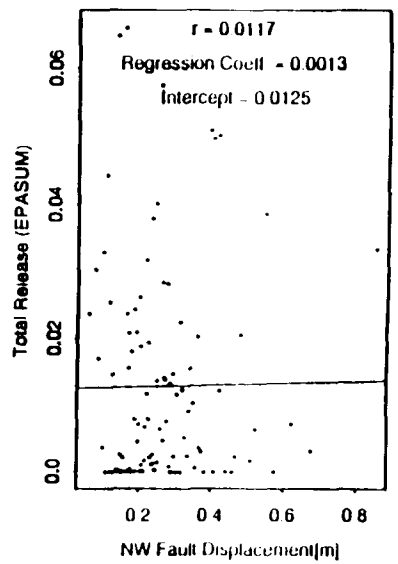
Parameter No. 9



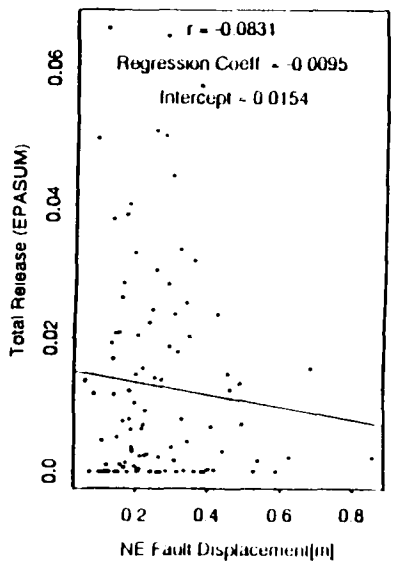
Parameter No. 10



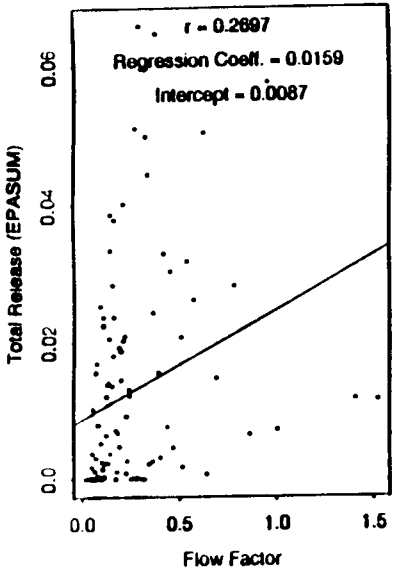
Parameter No. 11



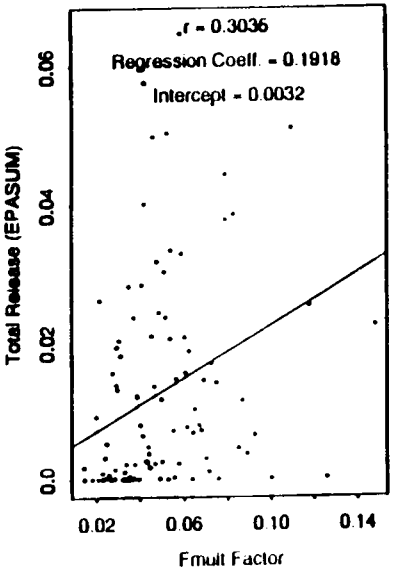
Parameter No. 12



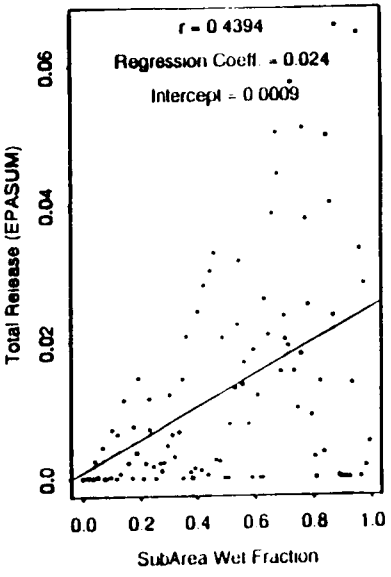
Parameter No. 13



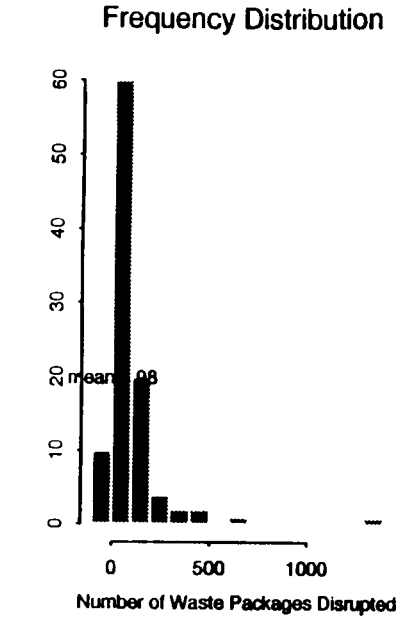
Parameter No. 14

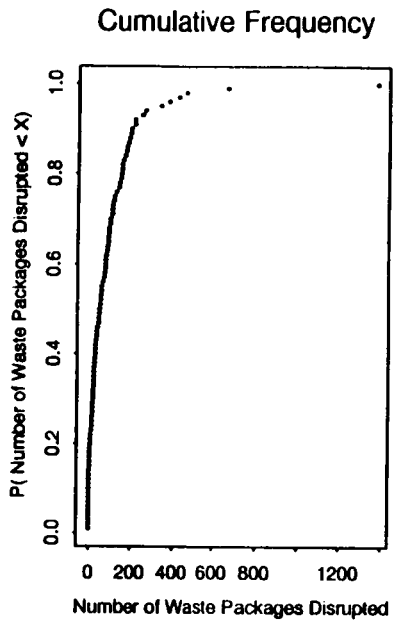


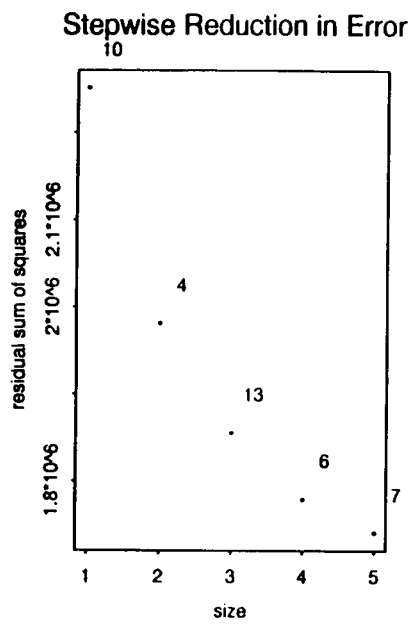
Parameter No. 15

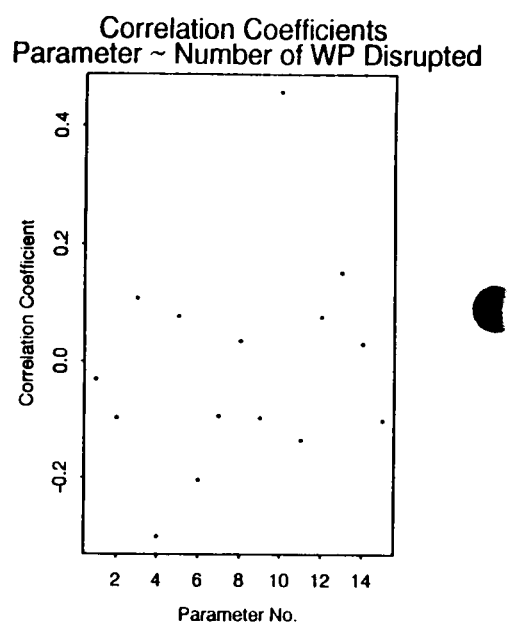


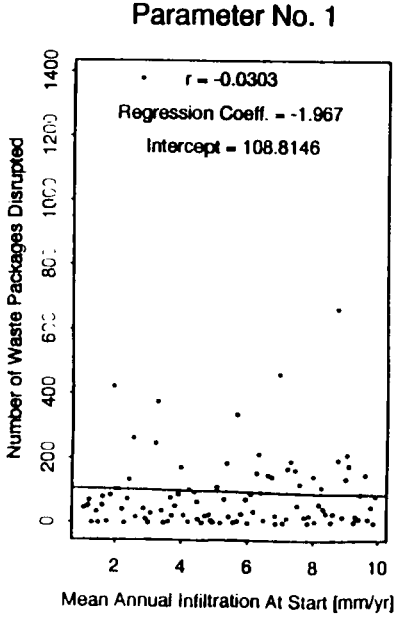
20 km Scenario
Summary Plots for Number of Waste Packages Disrupted

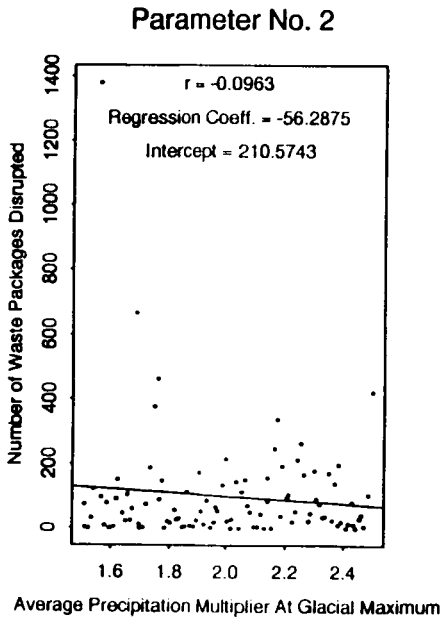


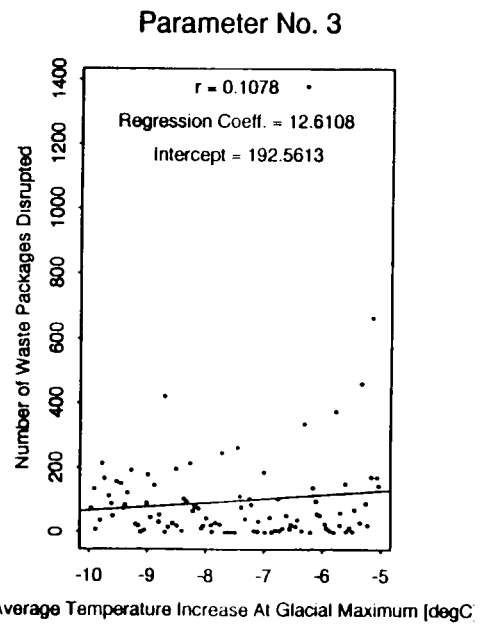


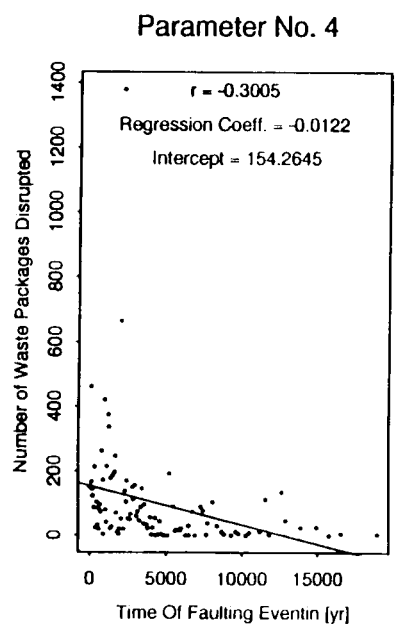




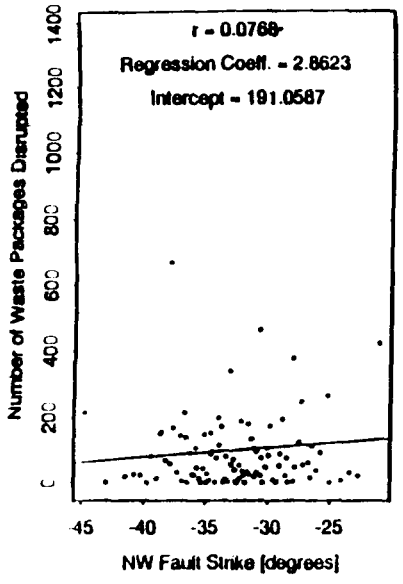




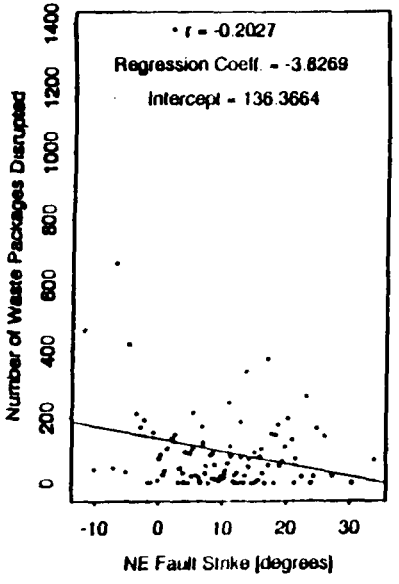




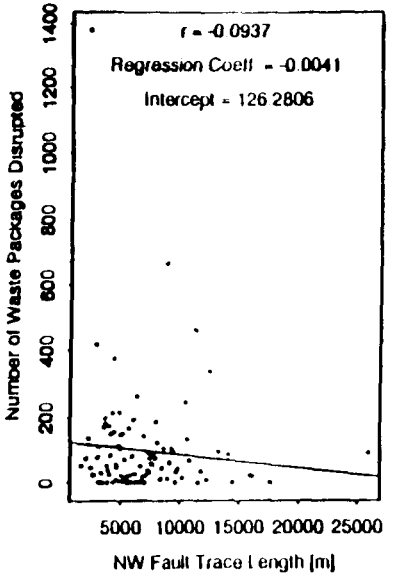
Parameter No. 5



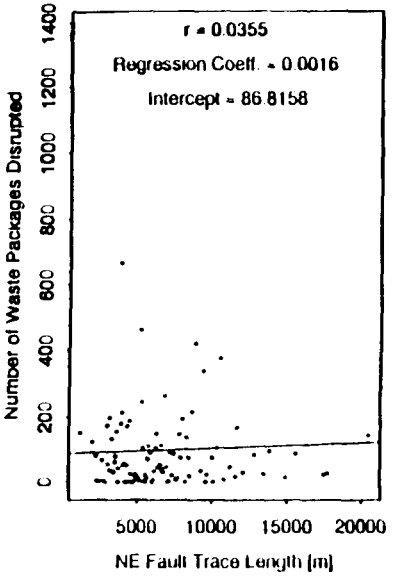
Parameter No. 6



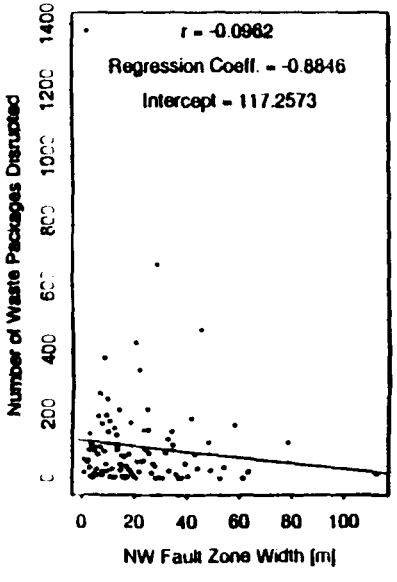
Parameter No. 7



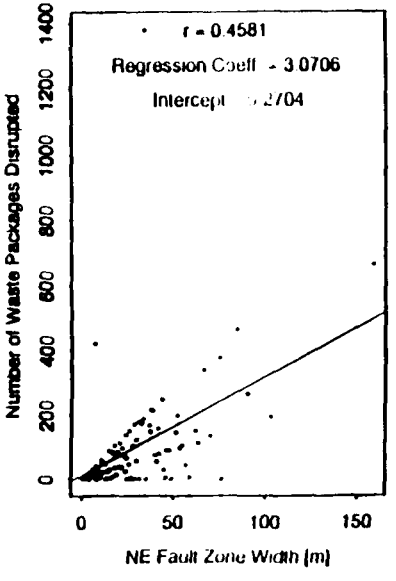
Parameter No. 8



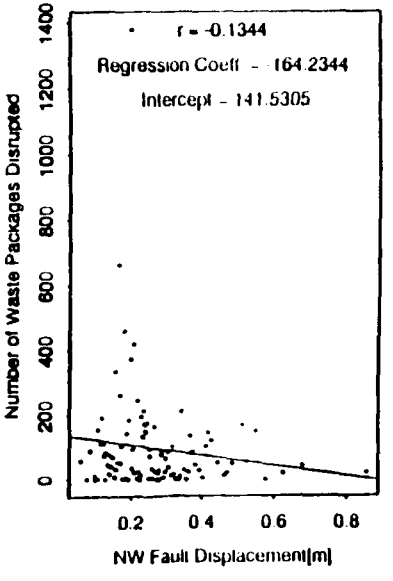
Parameter No. 9



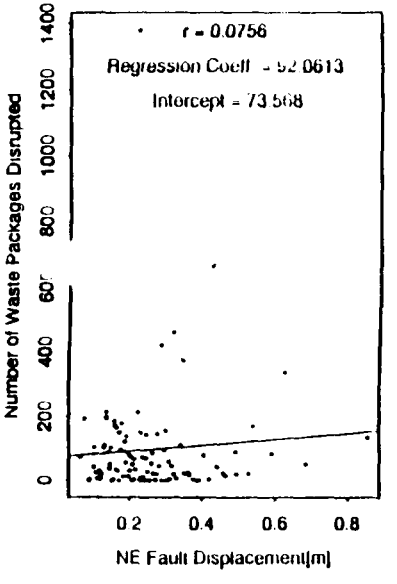
Parameter No. 10



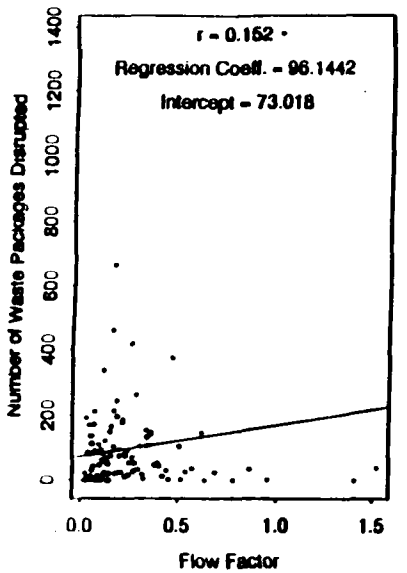
Parameter No. 11



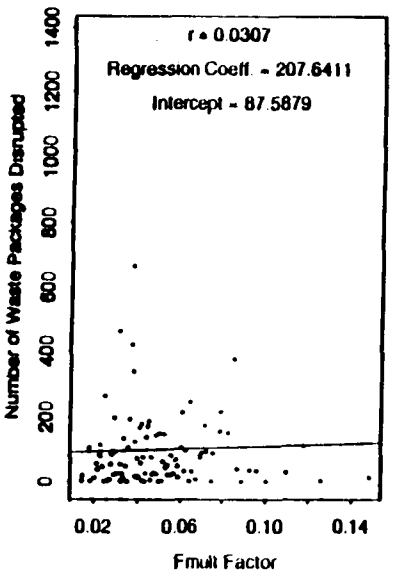
Parameter No. 12



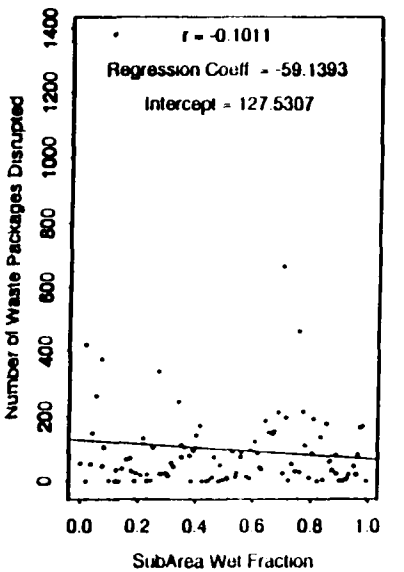
Parameter No. 13



Parameter No. 14



Parameter No. 15



64/64

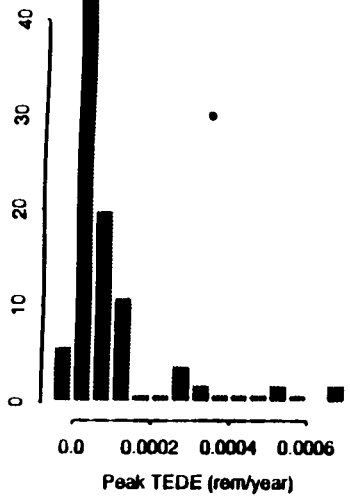
APPENDIX H

Run: FLTO_Run7

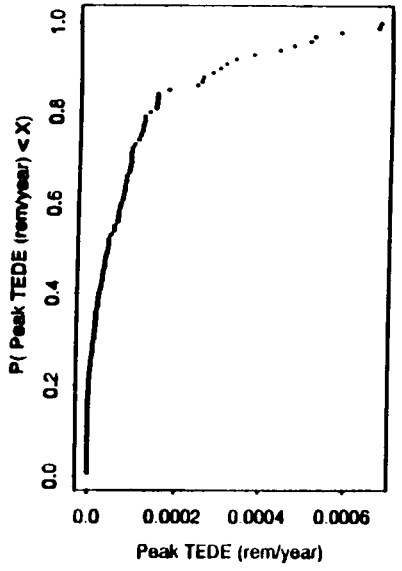
Distance to Critical Group = 20 km
Recurrence Interval = 200,000 yr
Only FAULTO, Localized Corrosion, Backfill

20 km Scenario
Summary Plots for Peak TEDE (rem/year)

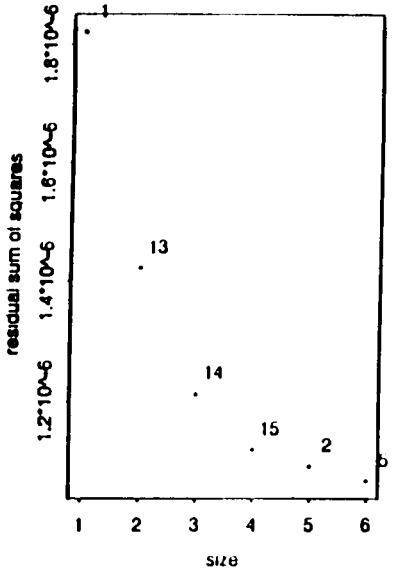
Frequency Distribution



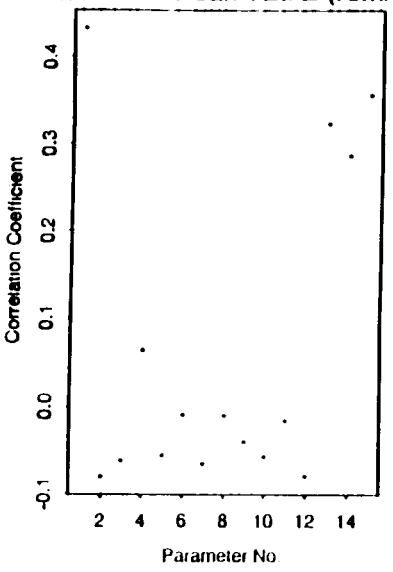
Cumulative Frequency



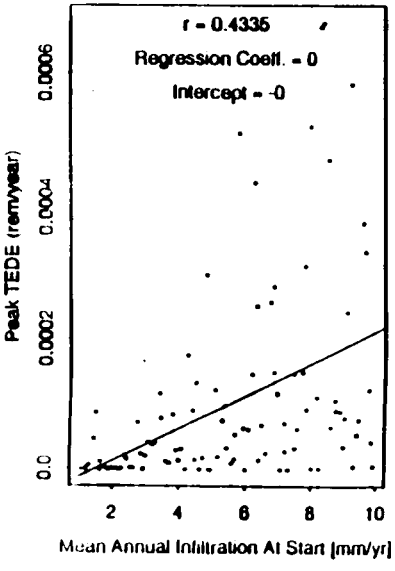
Stepwise Reduction in Error



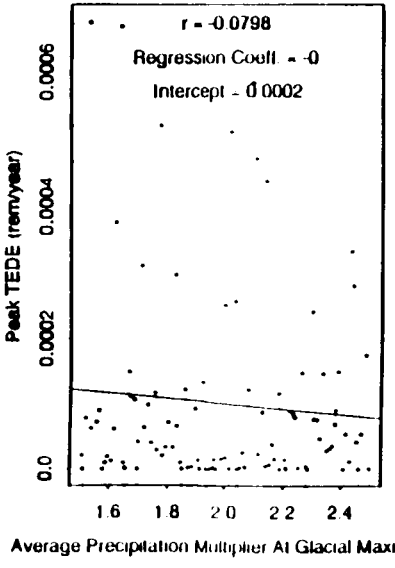
Correlation Coefficients
Parameter ~ Peak TEDE (rem/year)



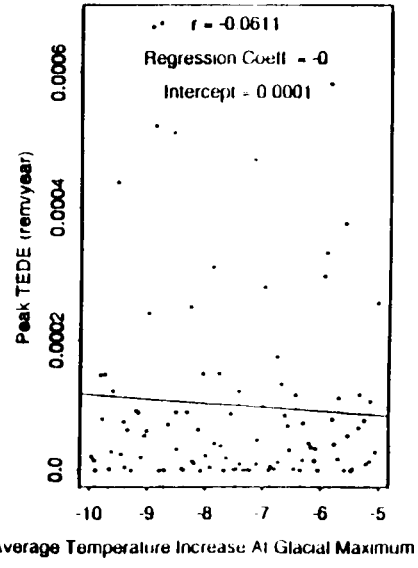
Parameter No. 1



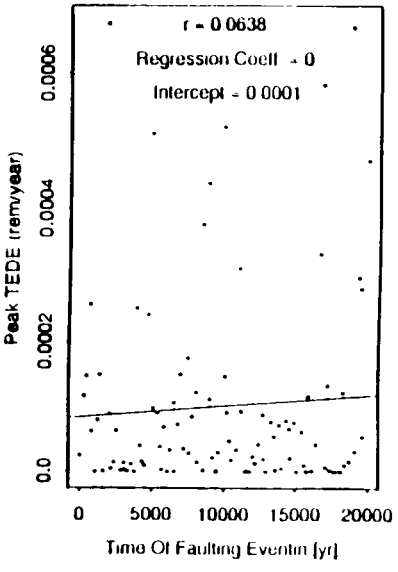
Parameter No. 2



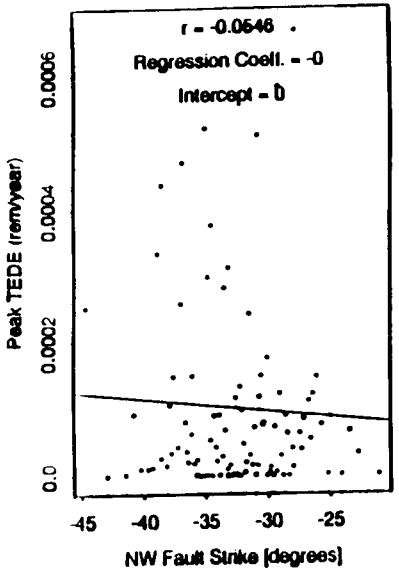
Parameter No. 3



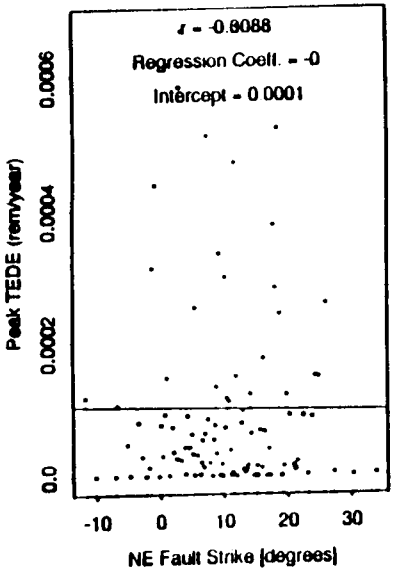
Parameter No. 4



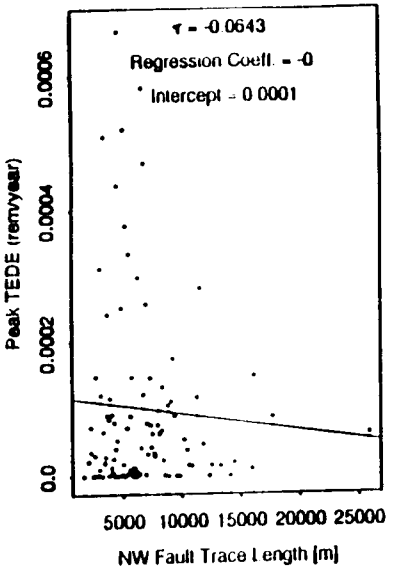
Parameter No. 5



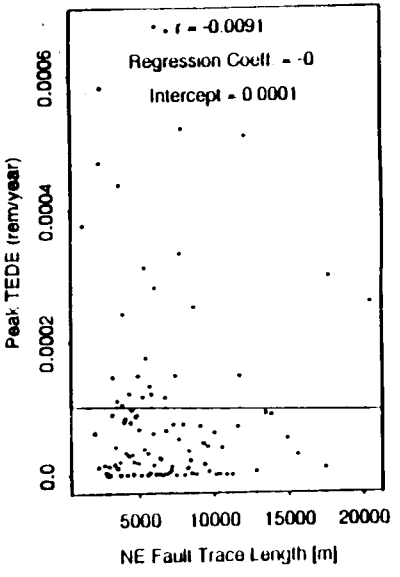
Parameter No. 6



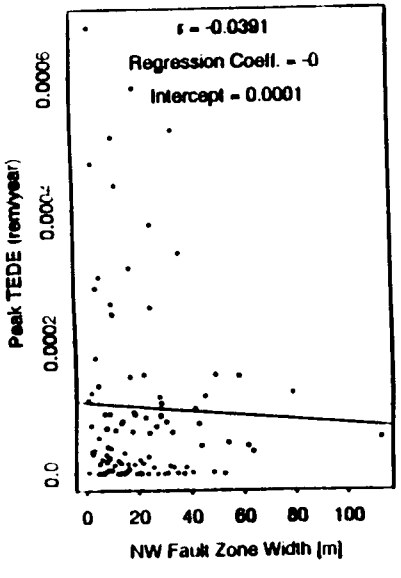
Parameter No. 7



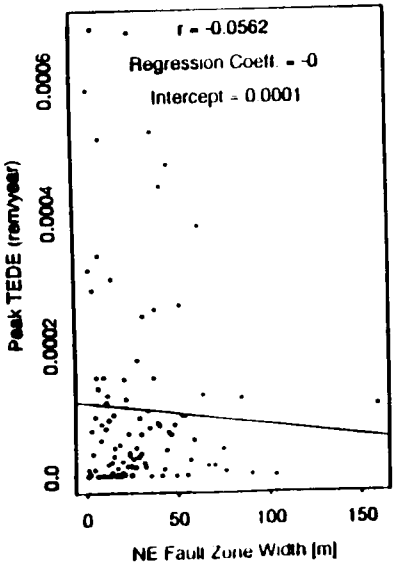
Parameter No. 8



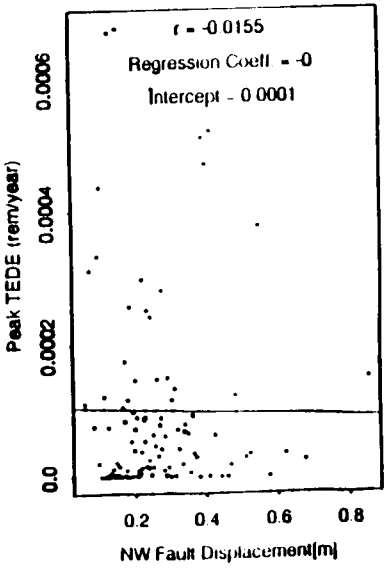
Parameter No. 9



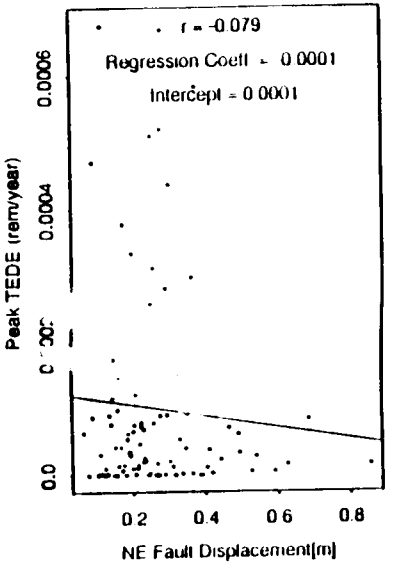
Parameter No. 10



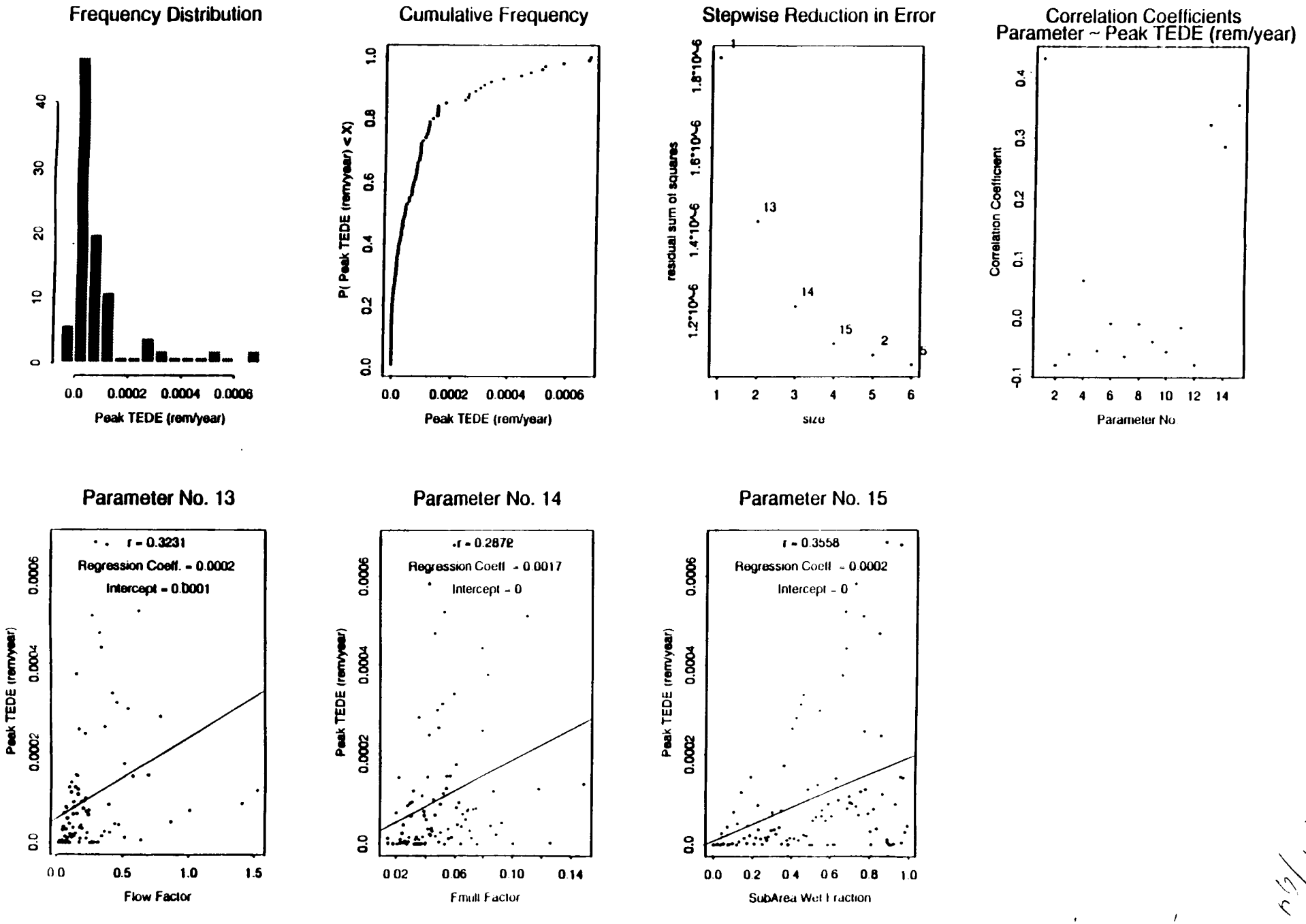
Parameter No. 11



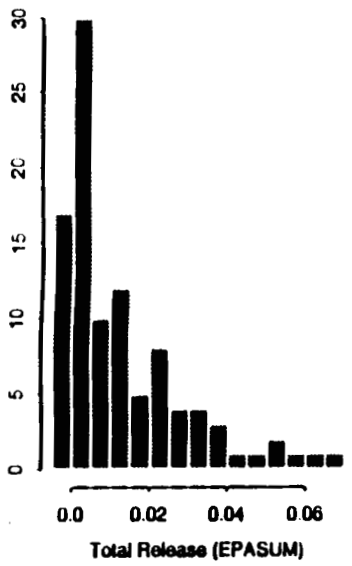
Parameter No. 12

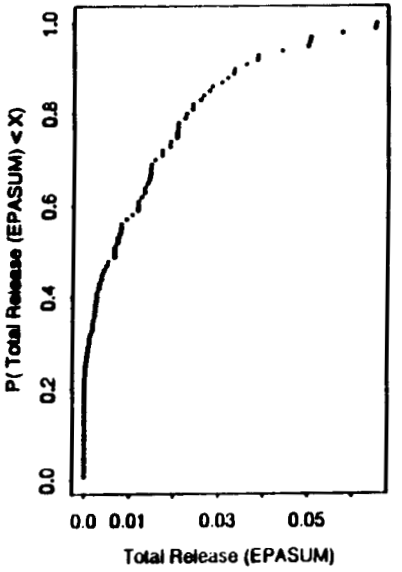


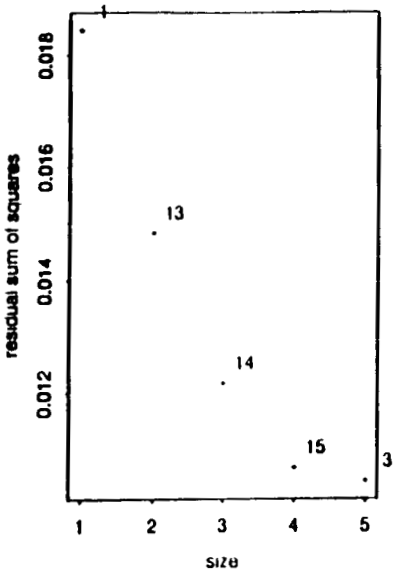
20 km Scenario
Summary Plots for Peak TEDE (rem/year)

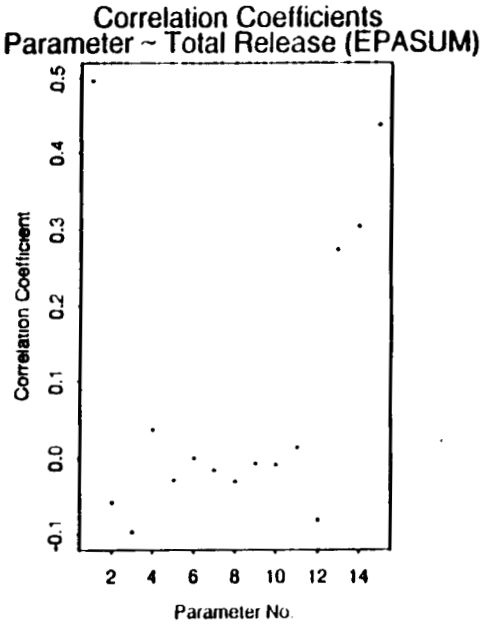


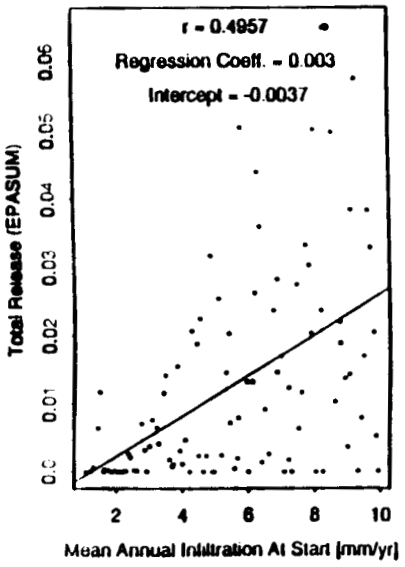
20 km Scenario
Summary Plots for Total Release (EPASUM)

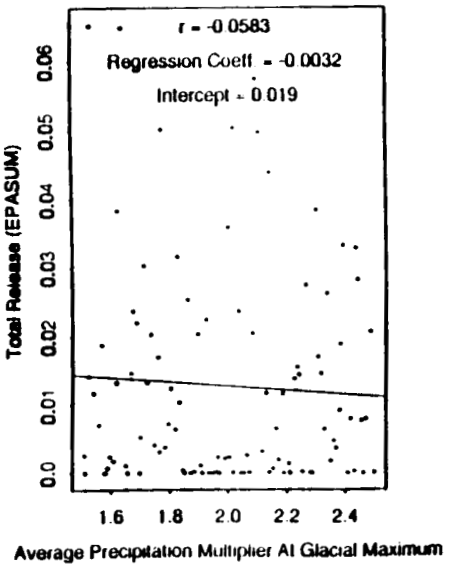


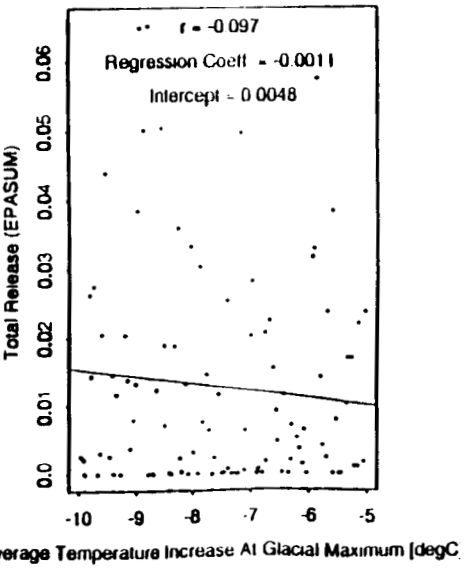


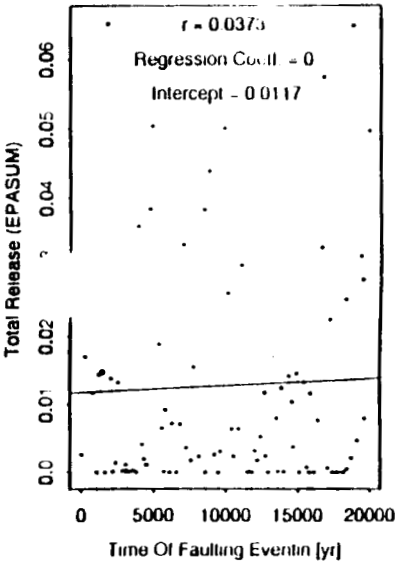




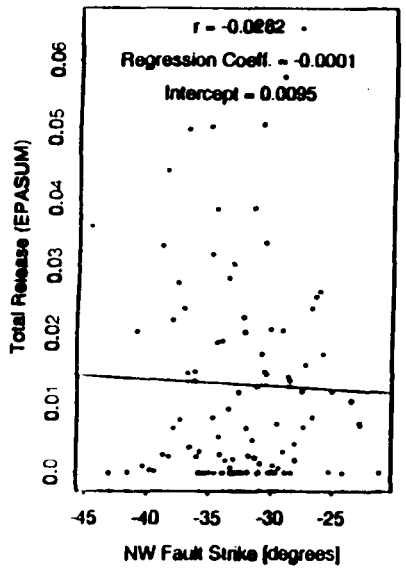




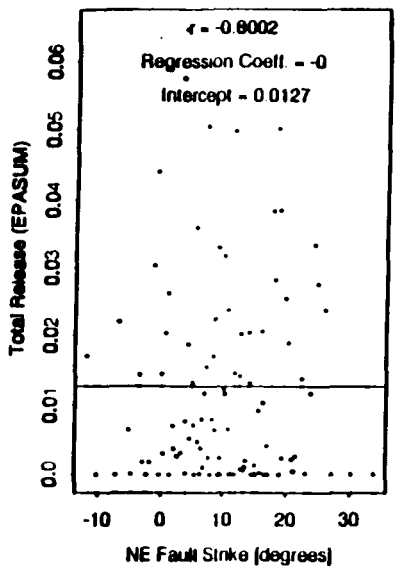




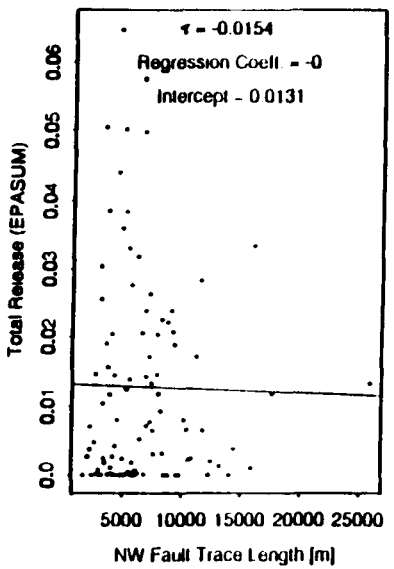
Parameter No. 5



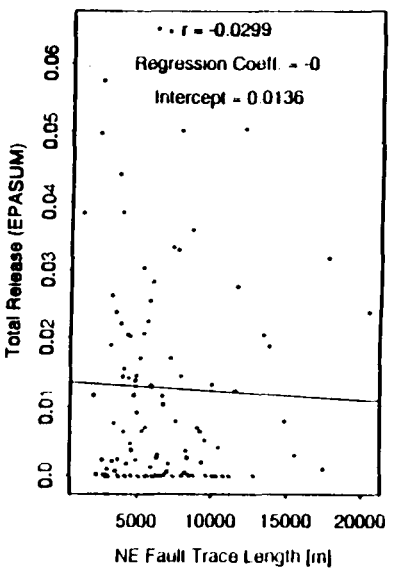
Parameter No. 6



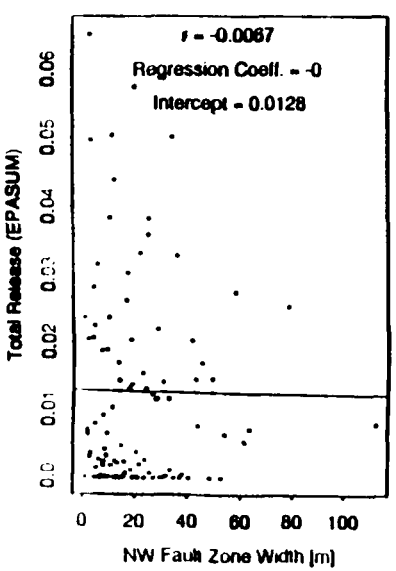
Parameter No. 7



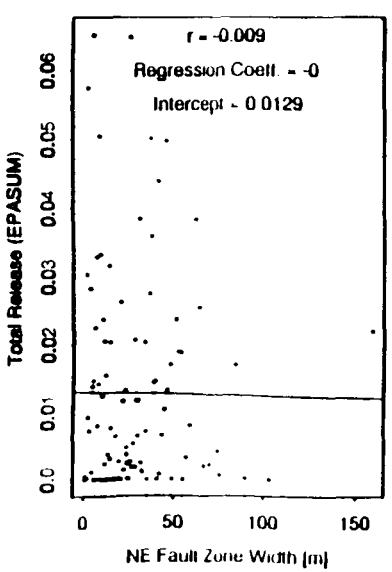
Parameter No. 8



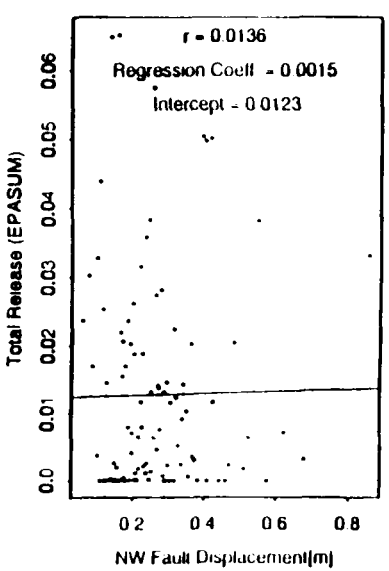
Parameter No. 9



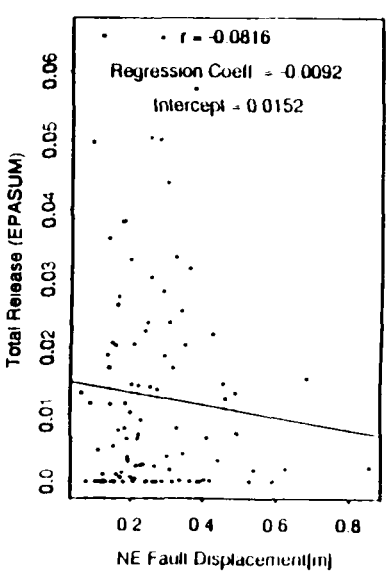
Parameter No. 10



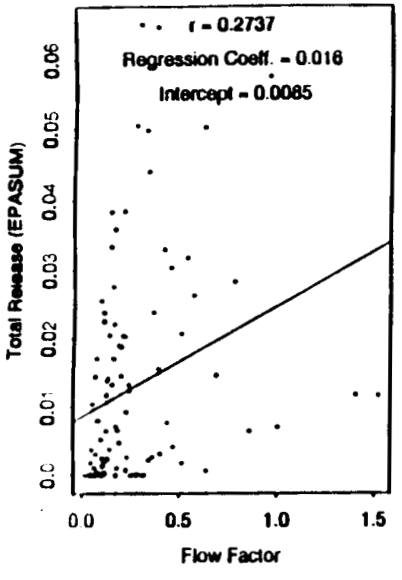
Parameter No. 11



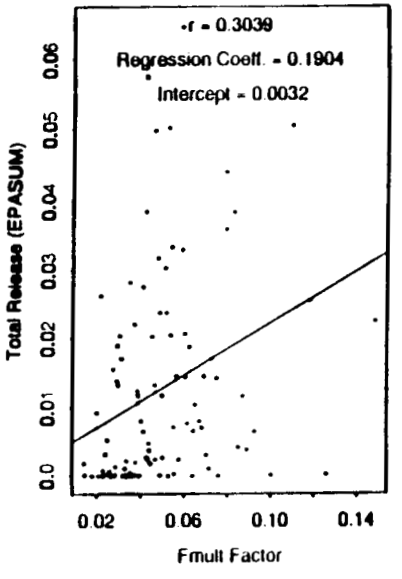
Parameter No. 12



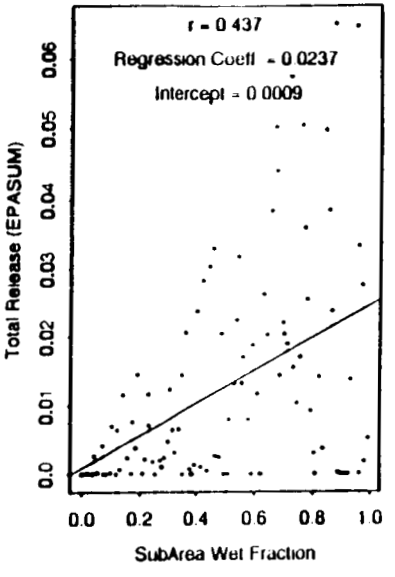
Parameter No. 13



Parameter No. 14

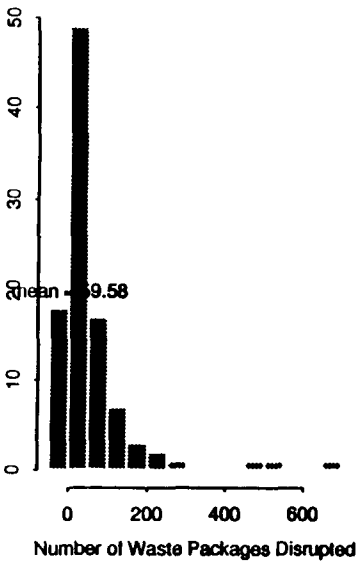


Parameter No. 15

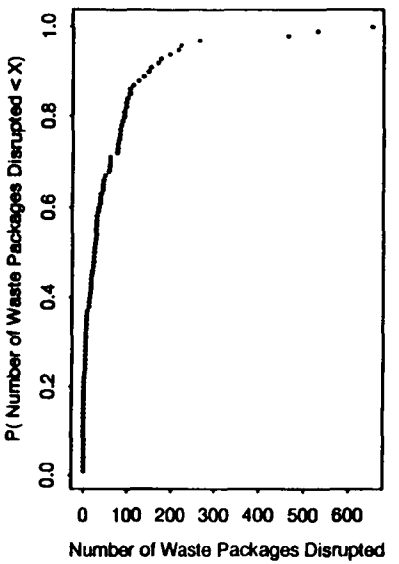


20 km Scenario
Summary Plots for Number of Waste Packages Disrupted

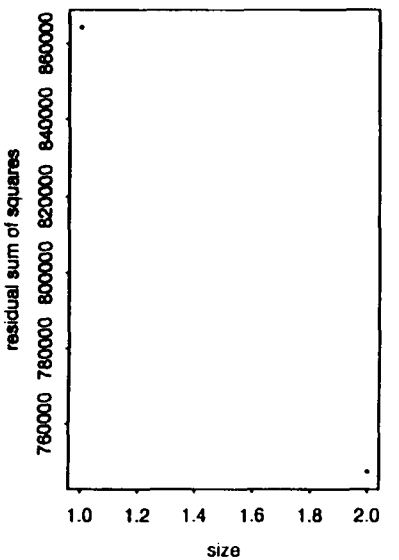
Frequency Distribution



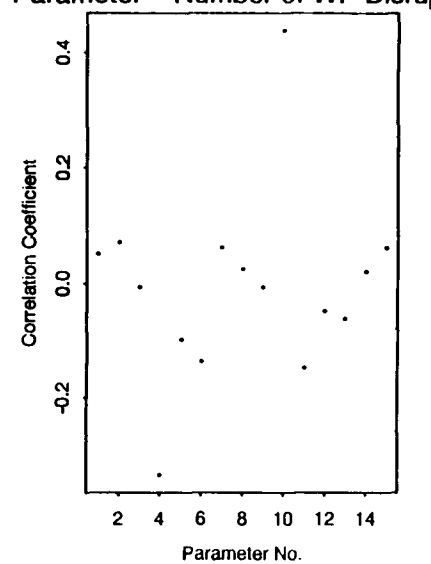
Cumulative Frequency



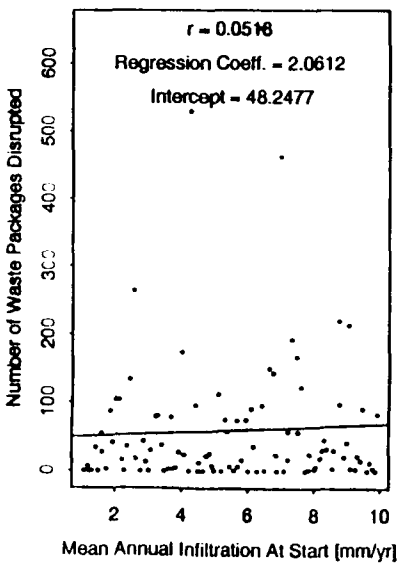
Stepwise Reduction in Error



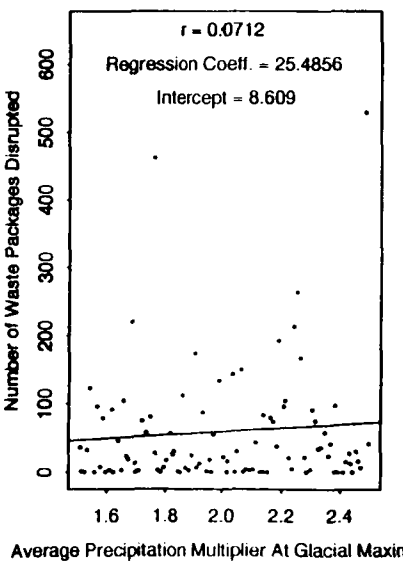
Correlation Coefficients
Parameter ~ Number of WP Disrupted



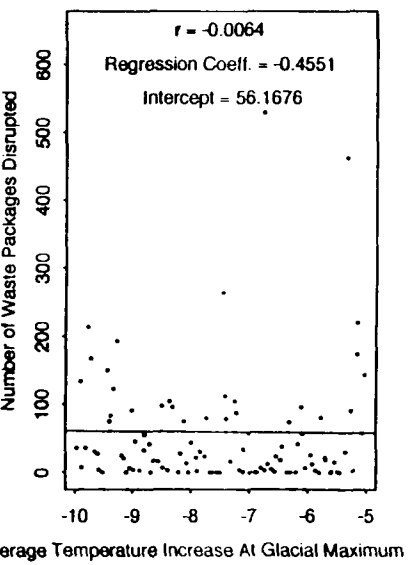
Parameter No. 1



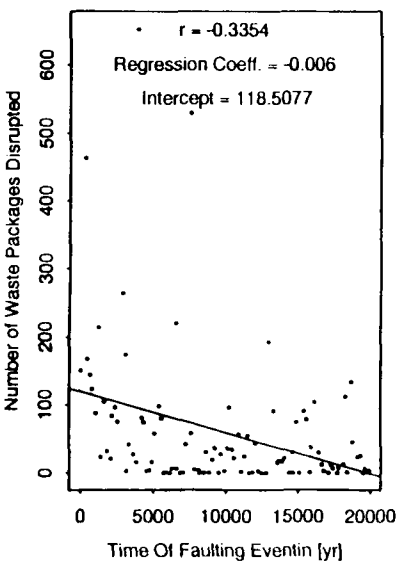
Parameter No. 2



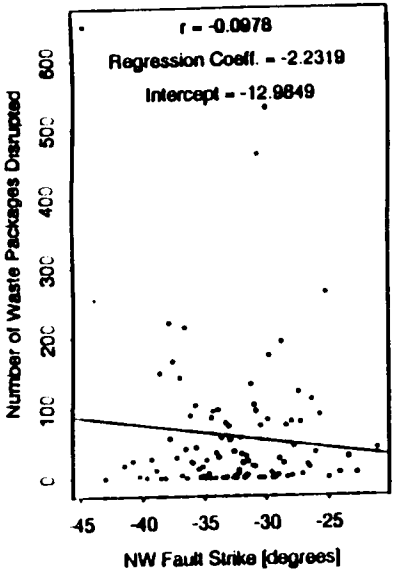
Parameter No. 3



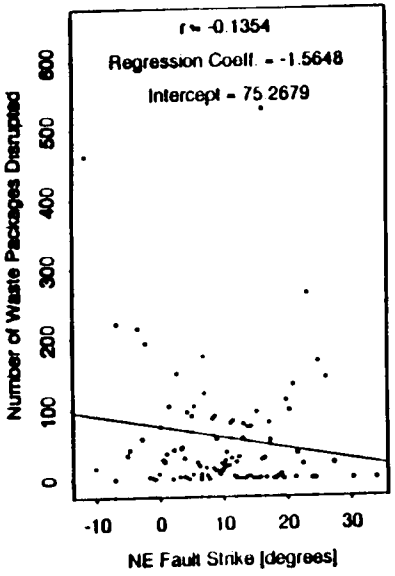
Parameter No. 4



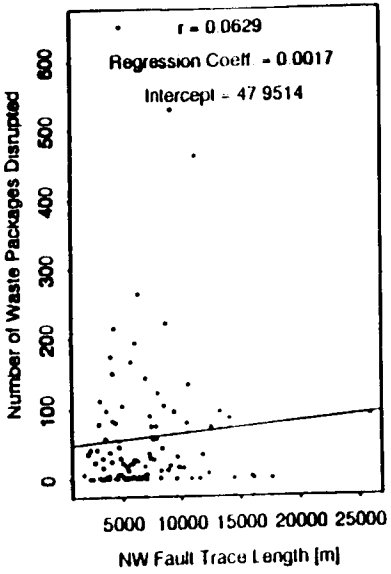
Parameter No. 5



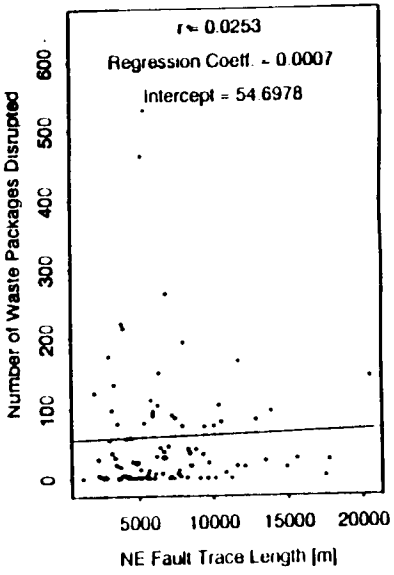
Parameter No. 6



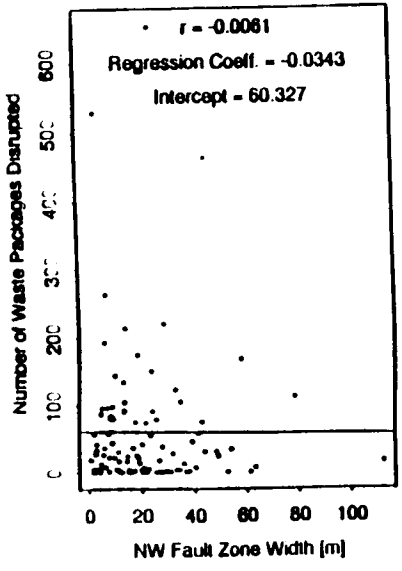
Parameter No. 7



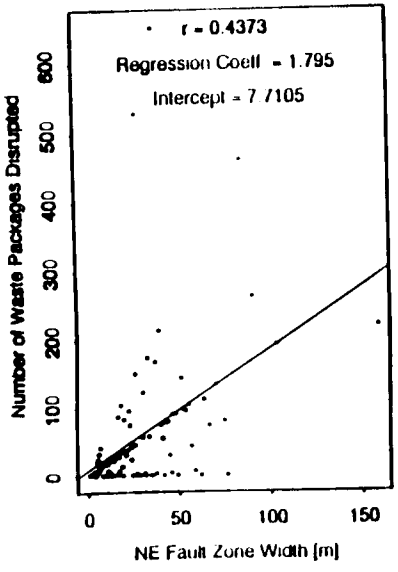
Parameter No. 8



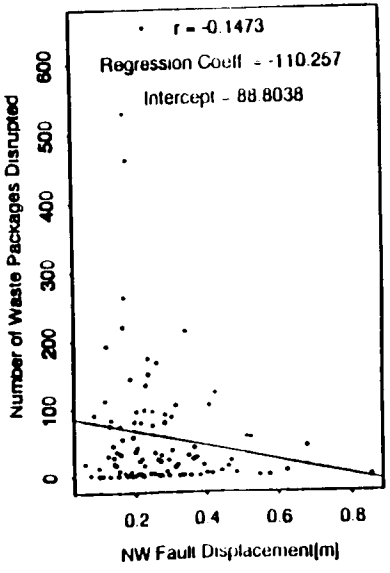
Parameter No. 9



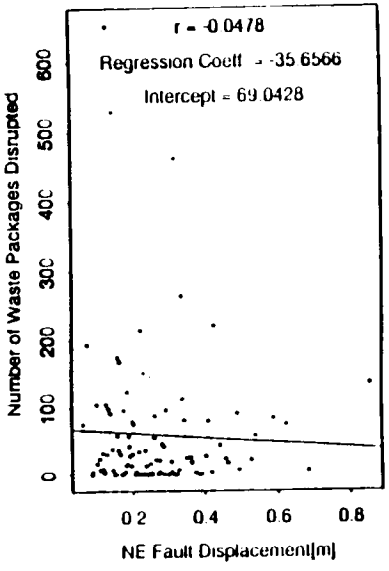
Parameter No. 10



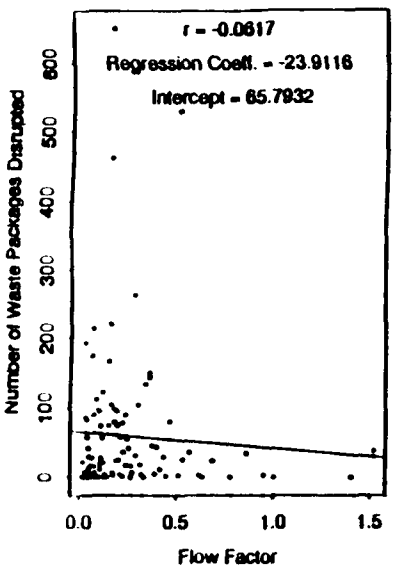
Parameter No. 11



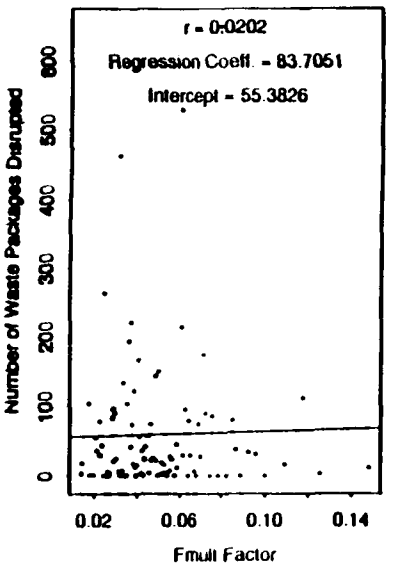
Parameter No. 12



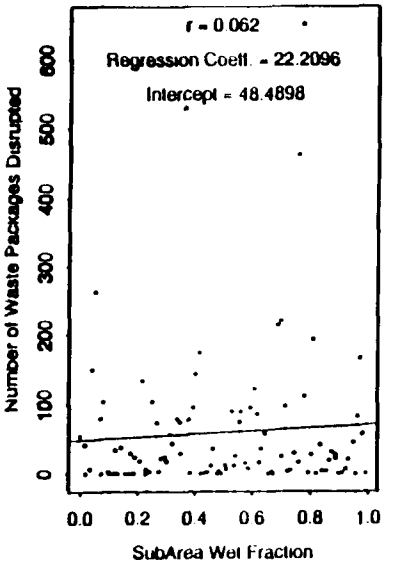
Parameter No. 13



Parameter No. 14



Parameter No. 15



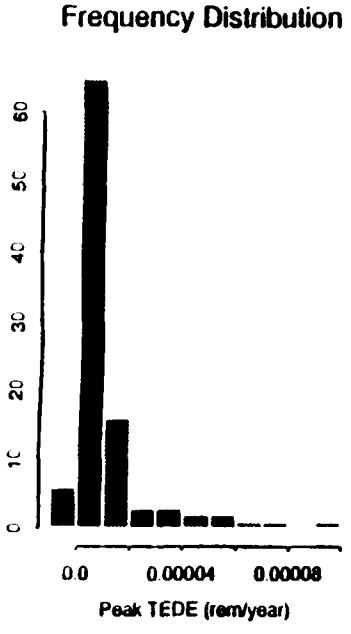
71/94

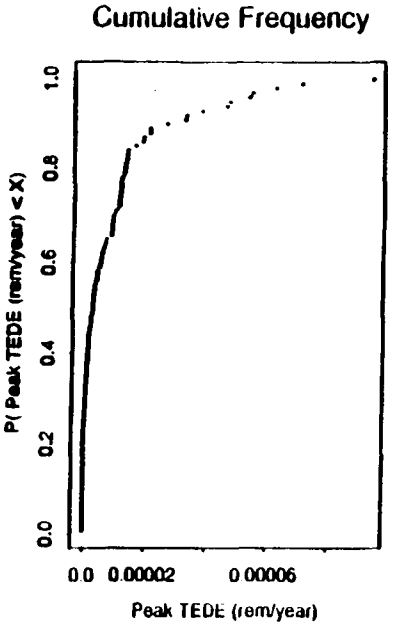
APPENDIX I

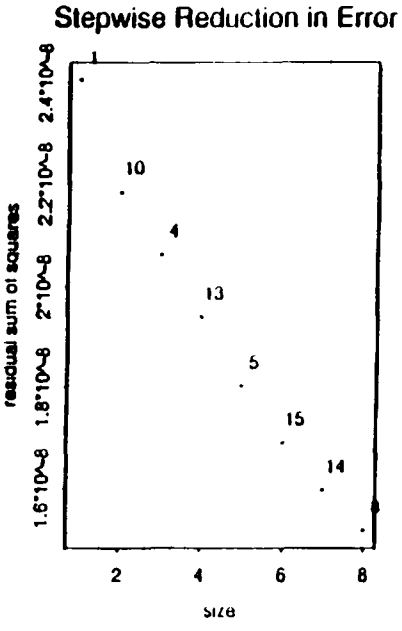
Run: FLTO_Run8

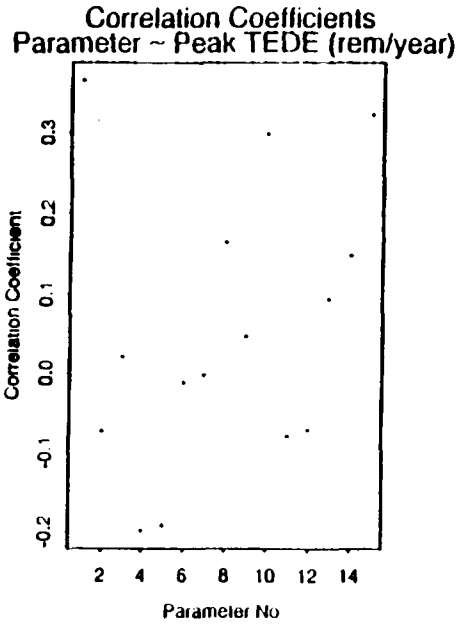
Distance to Critical Group = 20 km
Recurrence Interval = 5,000 yr
Only FAULTO, Uniform Corrosion, Backfill

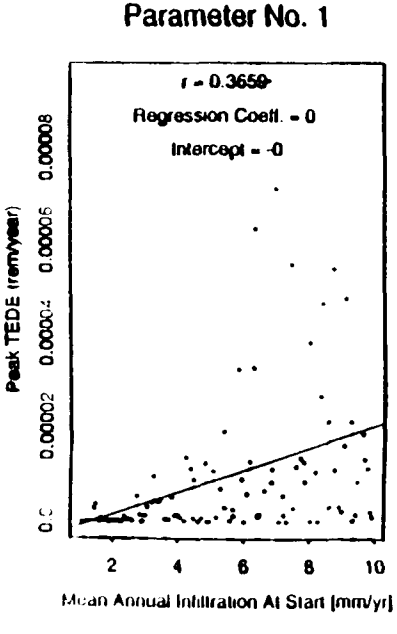
20 km Scenario
Summary Plots for Peak TEDE (rem/year)

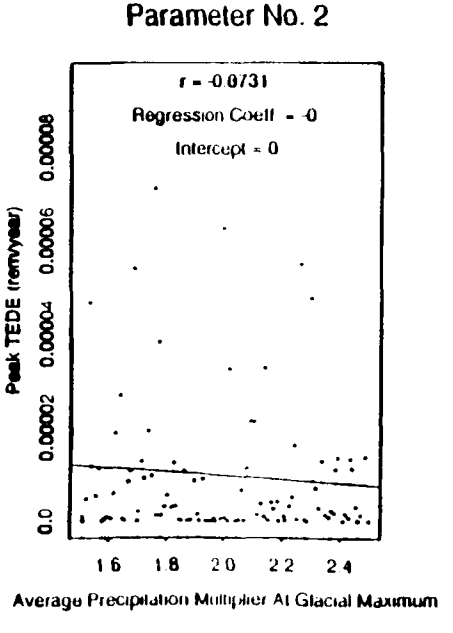


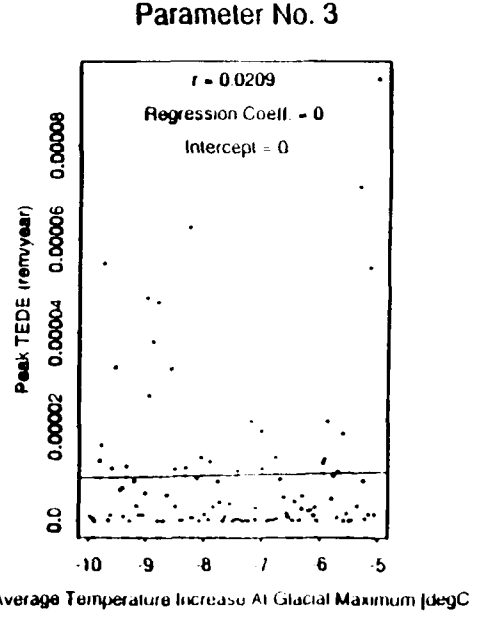


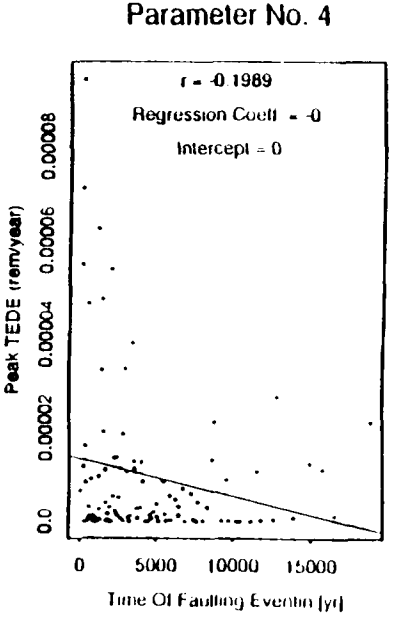




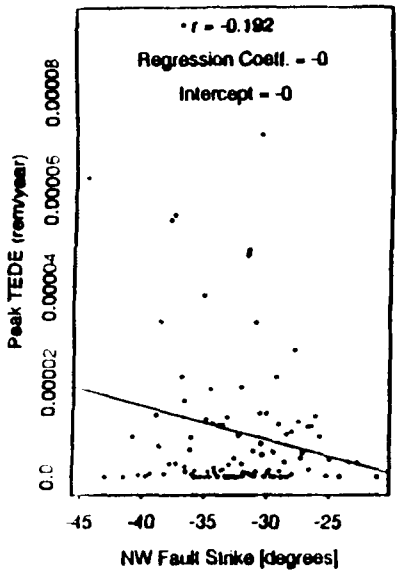




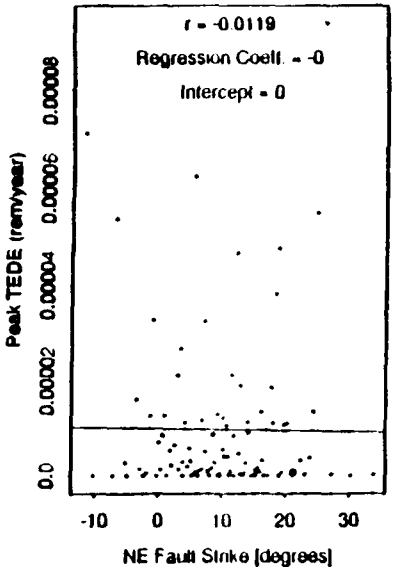




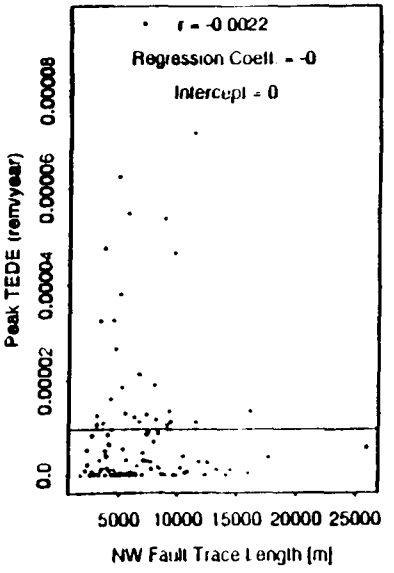
Parameter No. 5



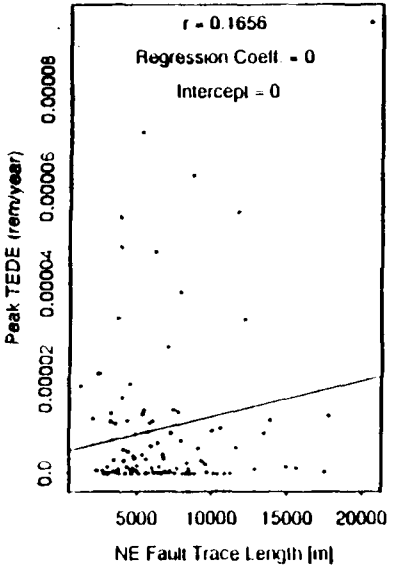
Parameter No. 6



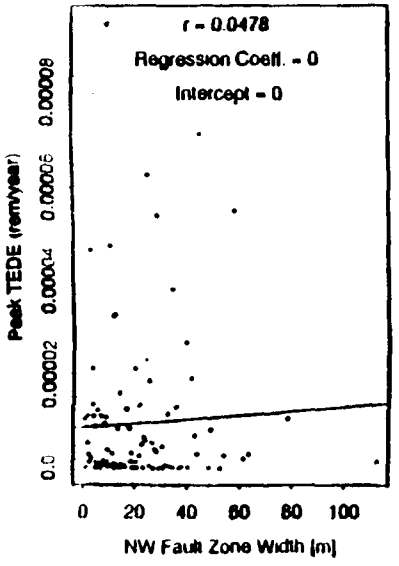
Parameter No. 7



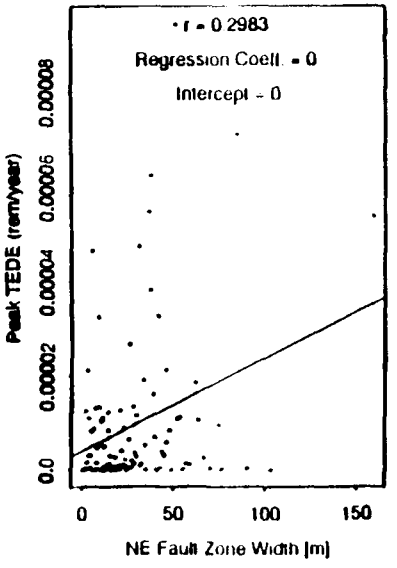
Parameter No. 8



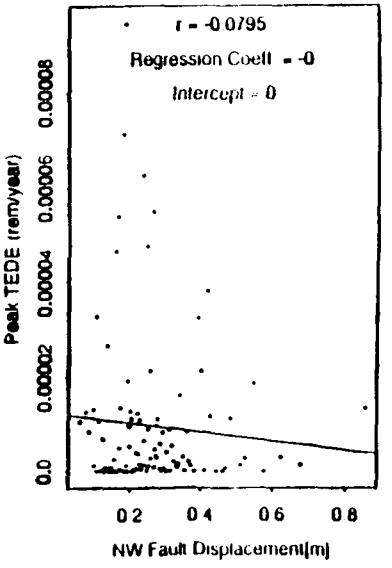
Parameter No. 9



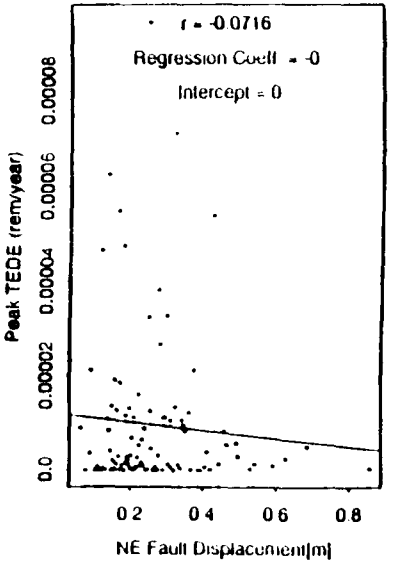
Parameter No. 10



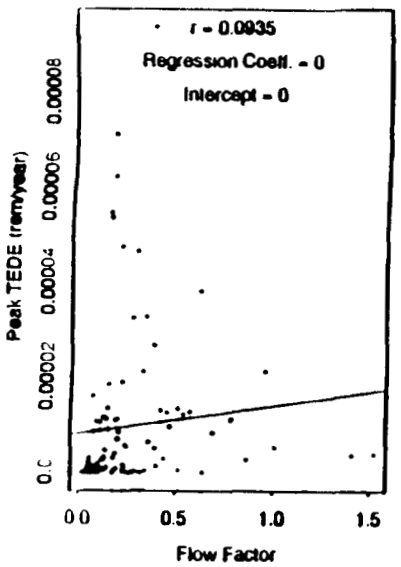
Parameter No. 11



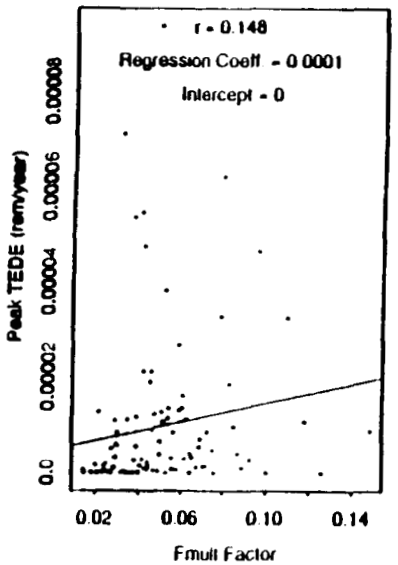
Parameter No. 12



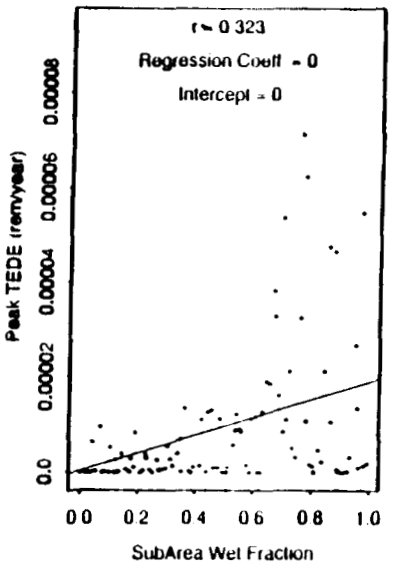
Parameter No. 13



Parameter No. 14



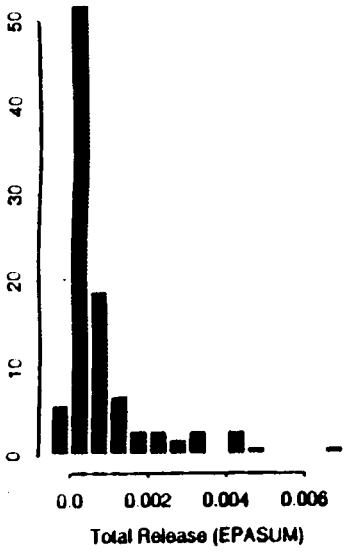
Parameter No. 15



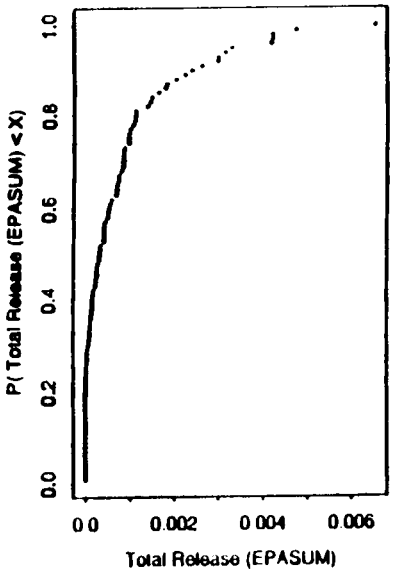
7/3/94

20 km Scenario
Summary Plots for Total Release (EPASUM)

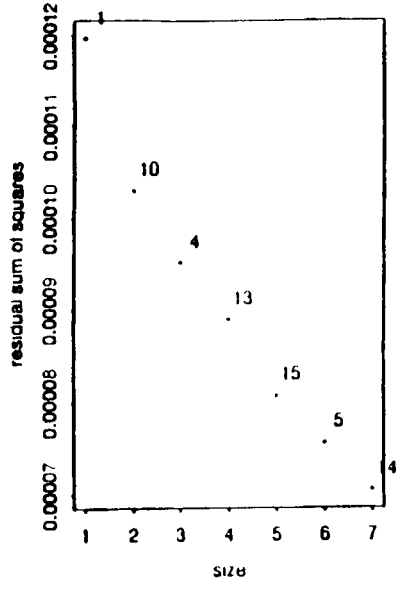
Frequency Distribution



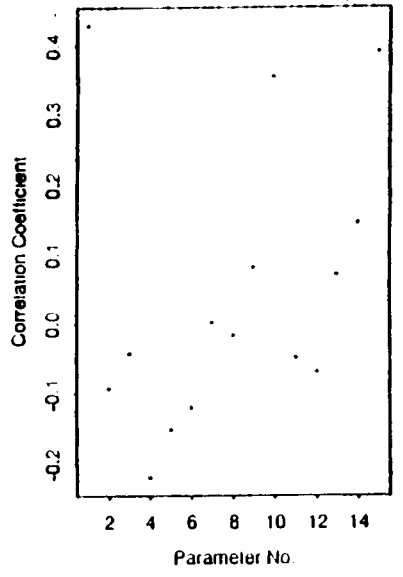
Cumulative Frequency



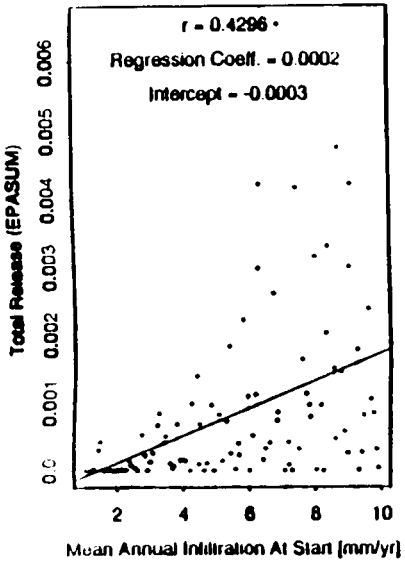
Stepwise Reduction in Error



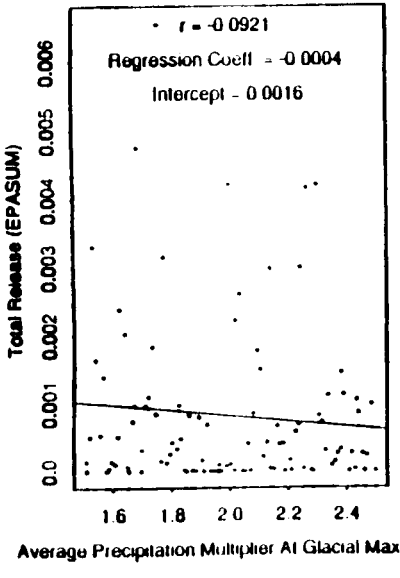
Correlation Coefficients
Parameter ~ Total Release (EPASUM)



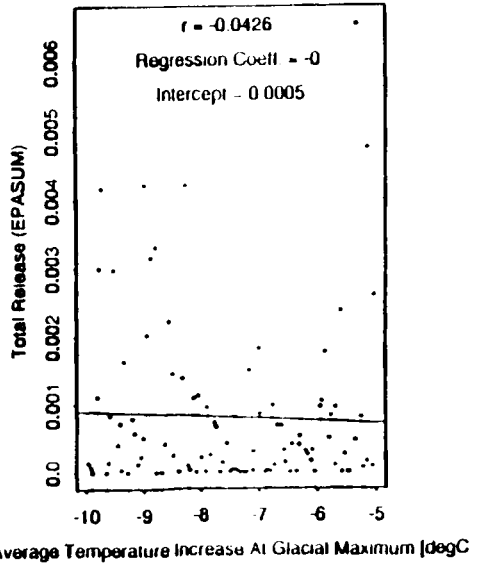
Parameter No. 1



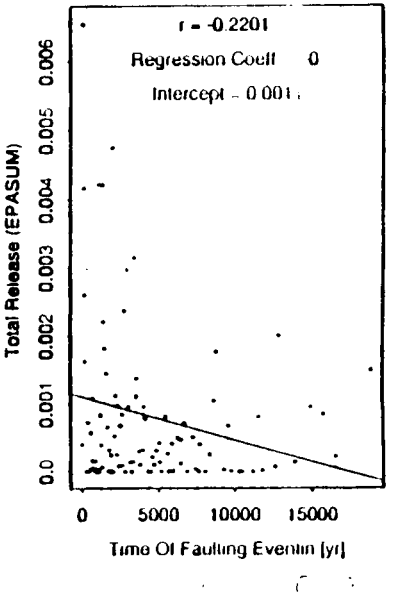
Parameter No. 2



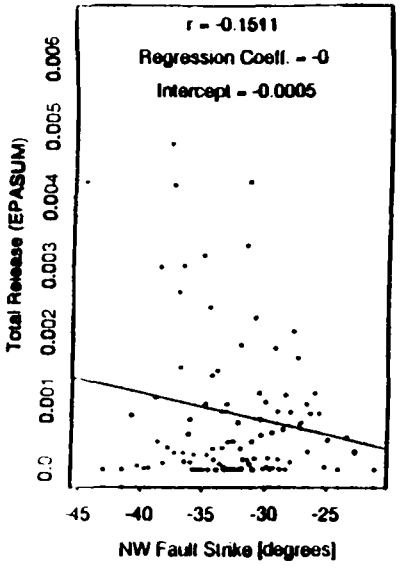
Parameter No. 3



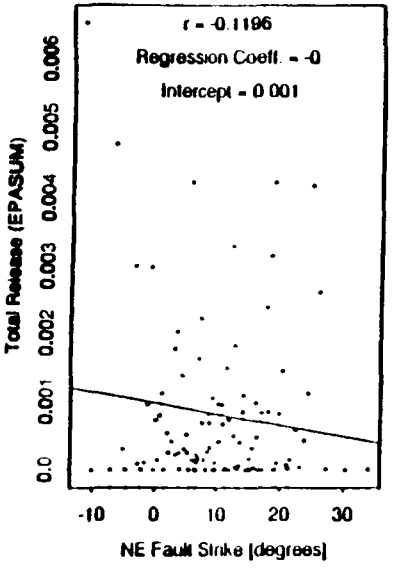
Parameter No. 4



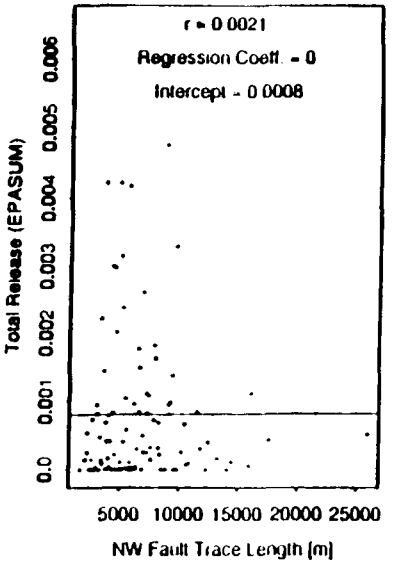
Parameter No. 5



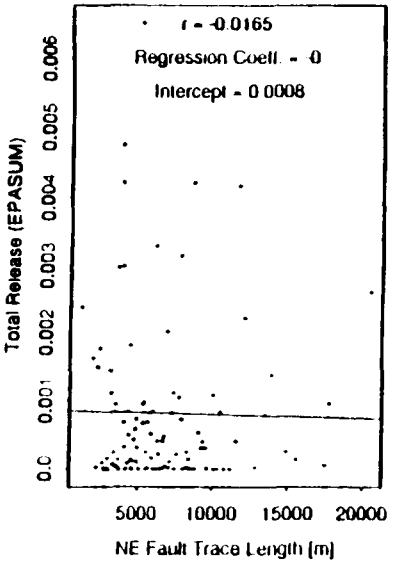
Parameter No. 6



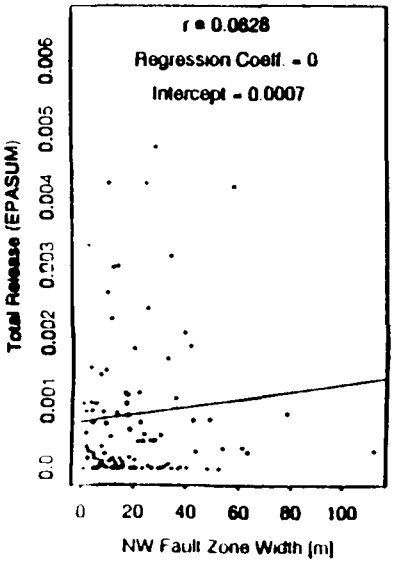
Parameter No. 7



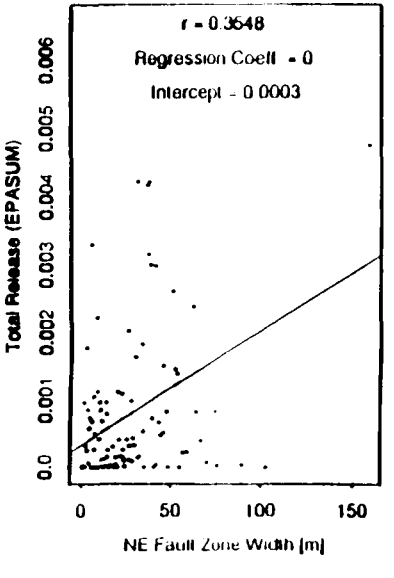
Parameter No. 8



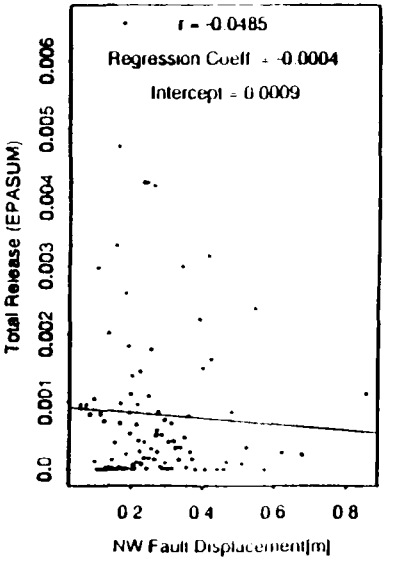
Parameter No. 9



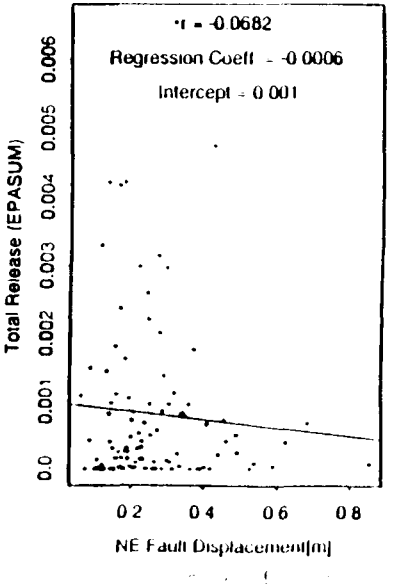
Parameter No. 10



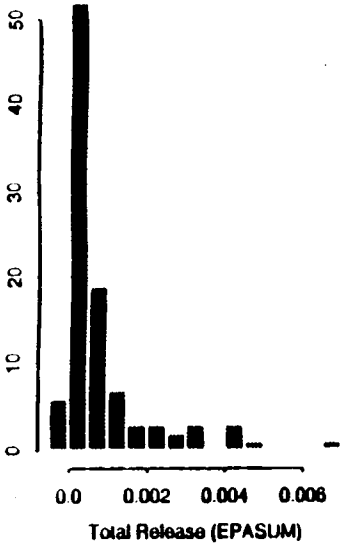
Parameter No. 11

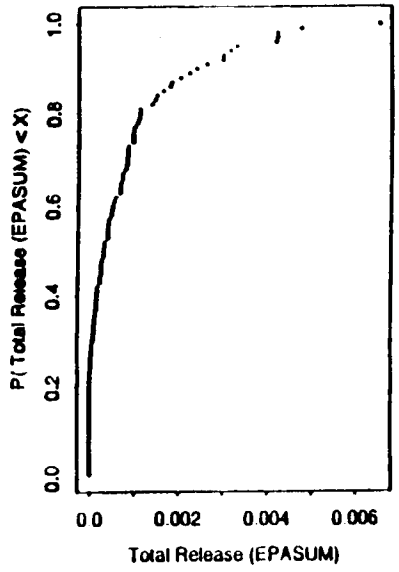


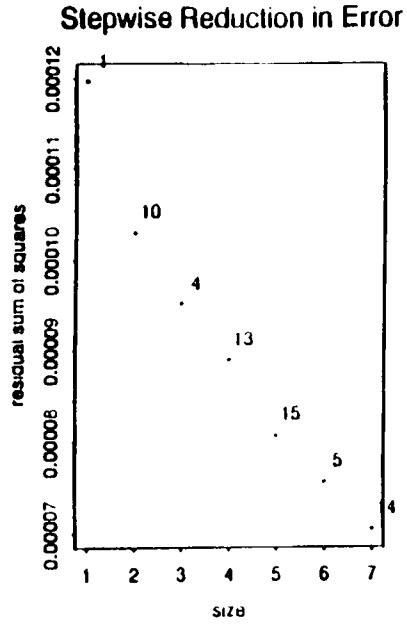
Parameter No. 12

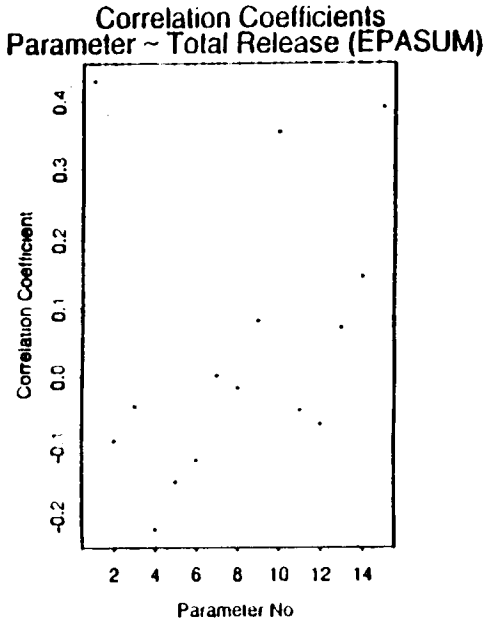


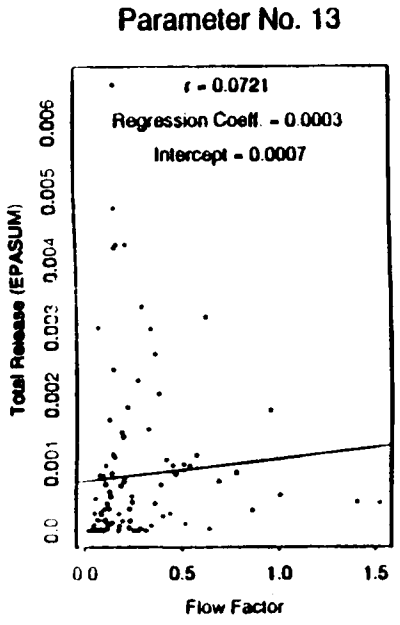
20 km Scenario
Summary Plots for Total Release (EPASUM)

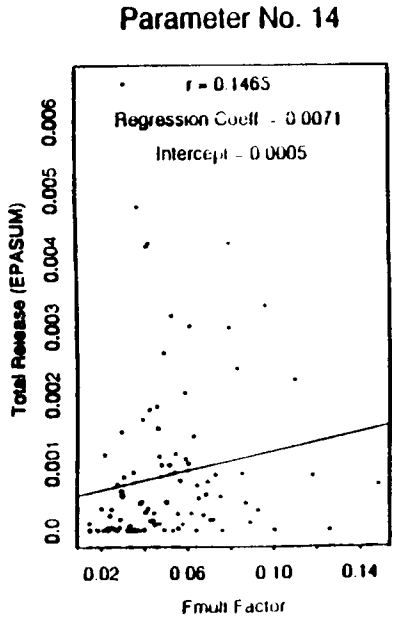


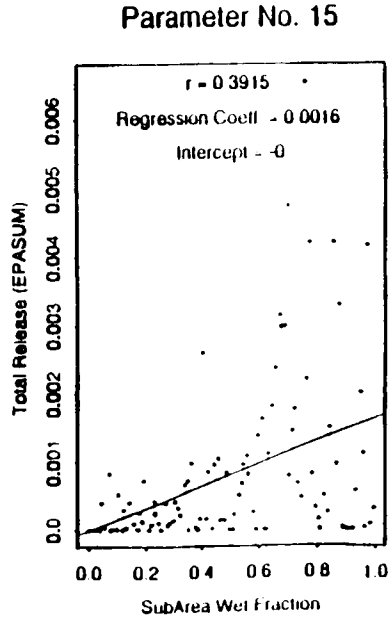




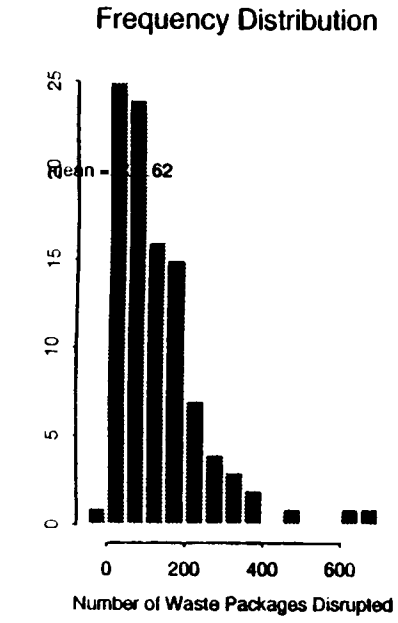


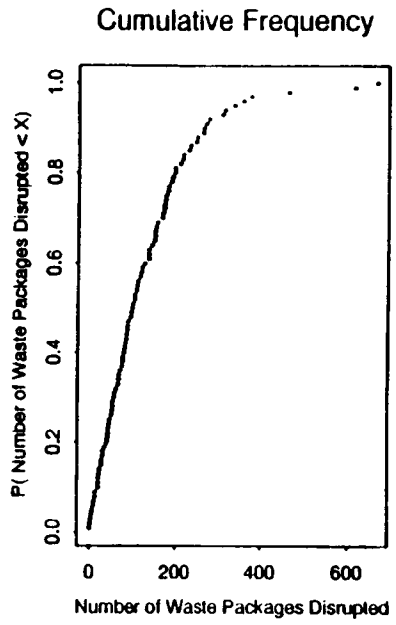


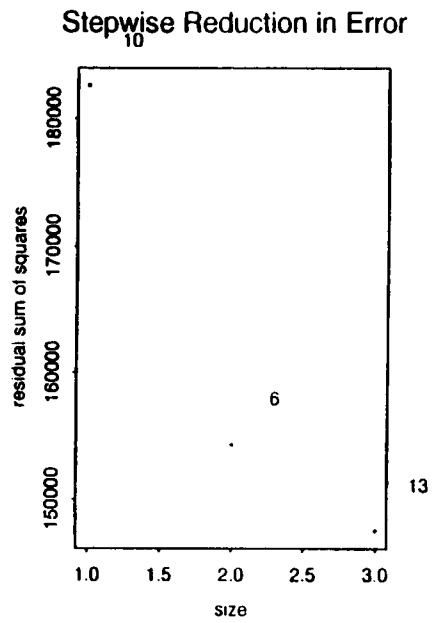


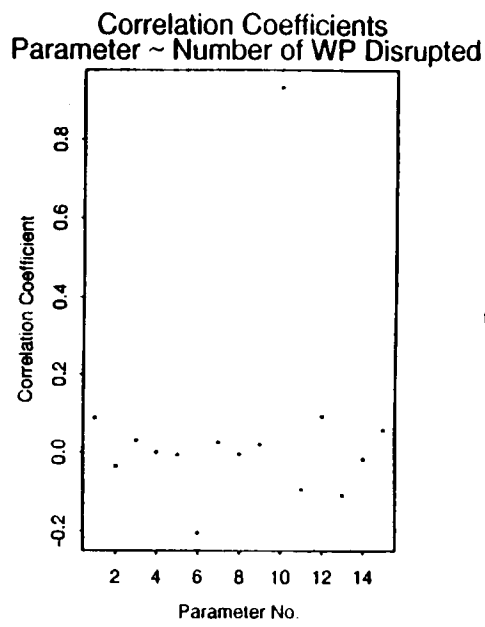


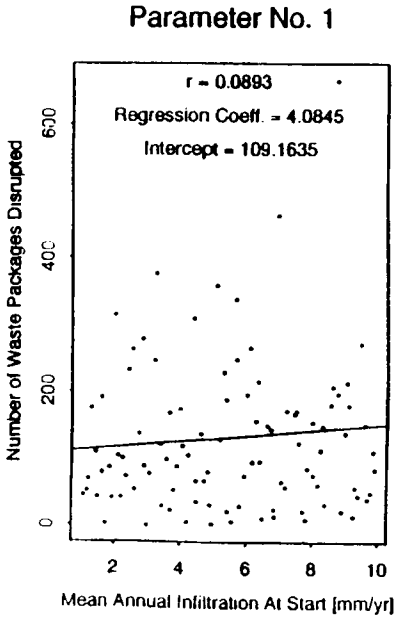
20 km Scenario
Summary Plots for Number of Waste Packages Disrupted

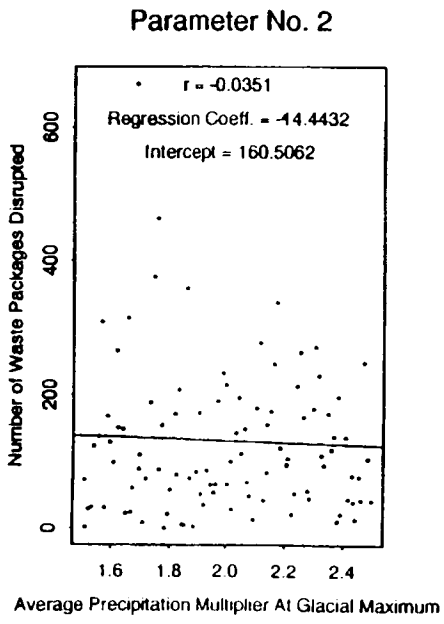


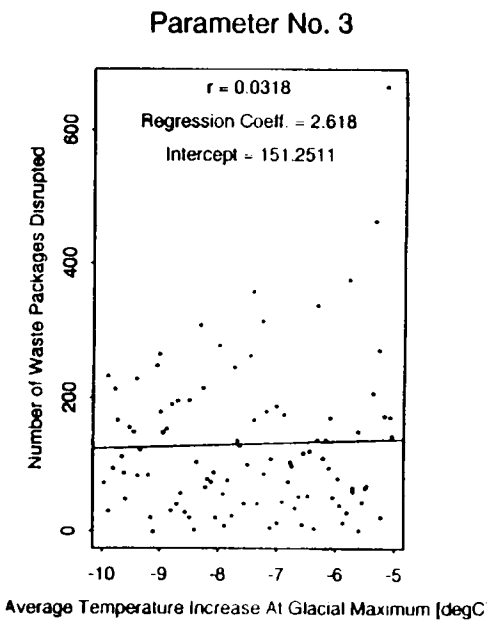


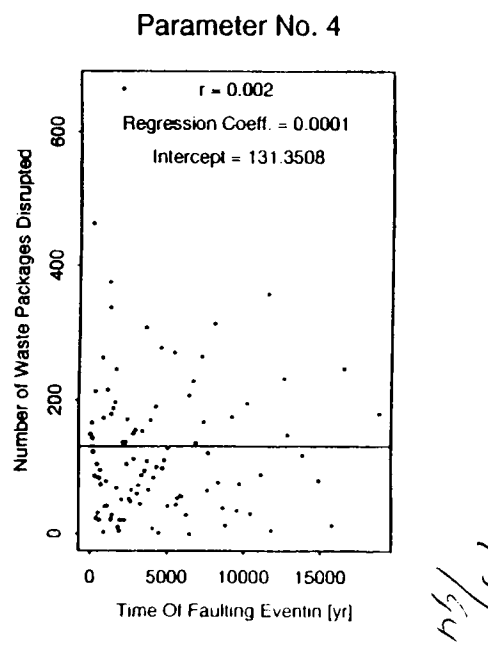




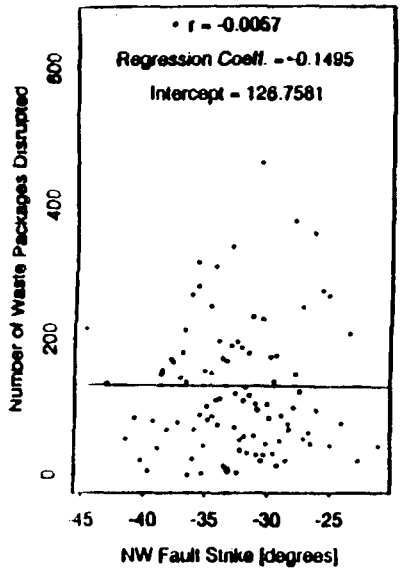




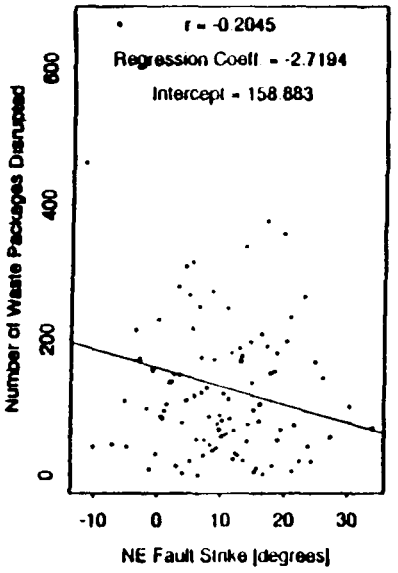




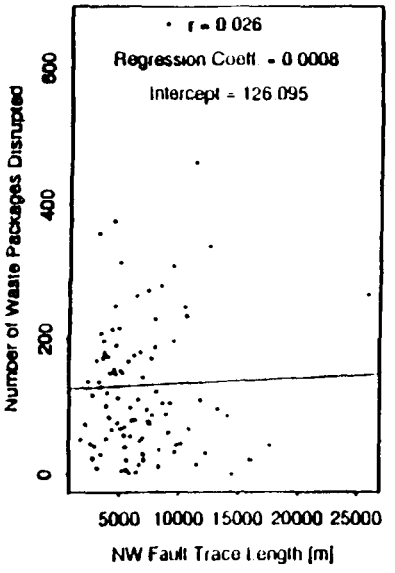
Parameter No. 5



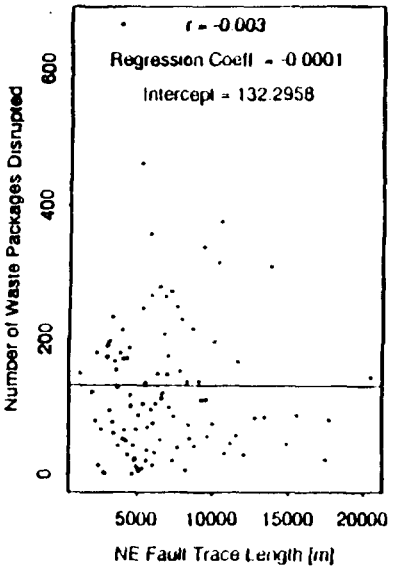
Parameter No. 6



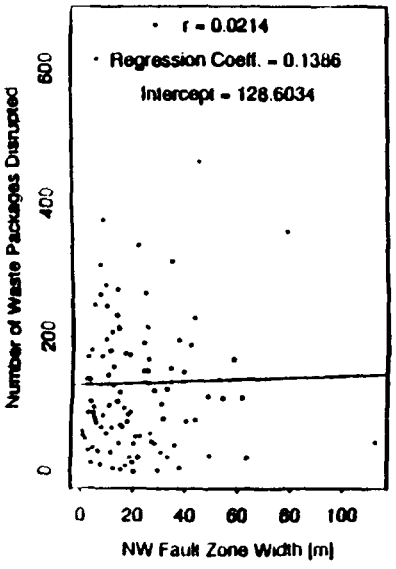
Parameter No. 7



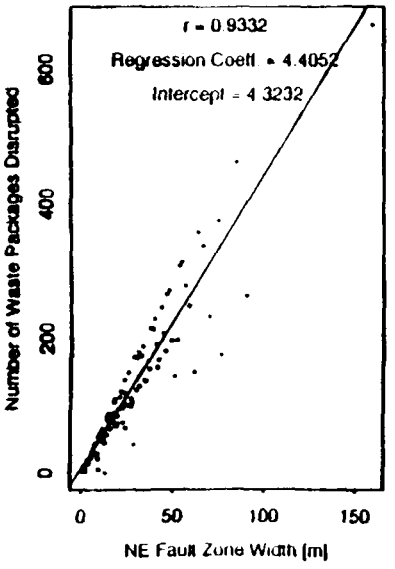
Parameter No. 8



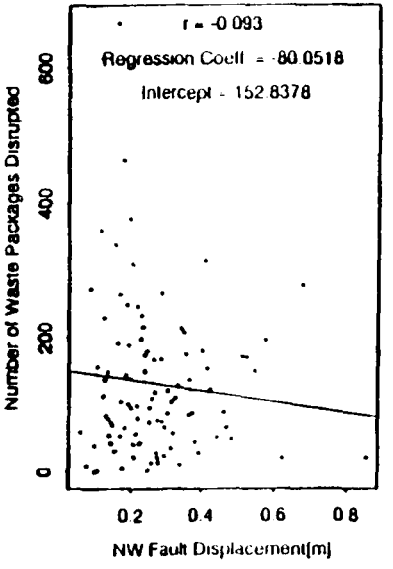
Parameter No. 9



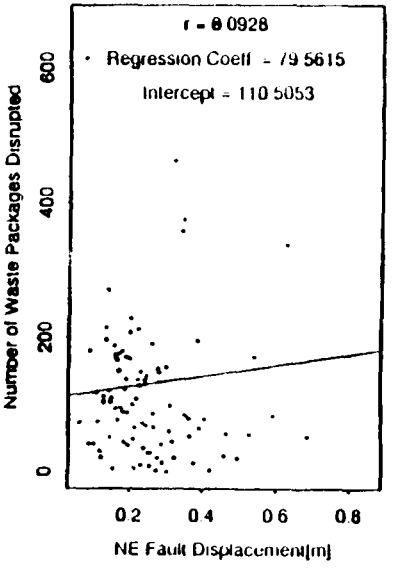
Parameter No. 10



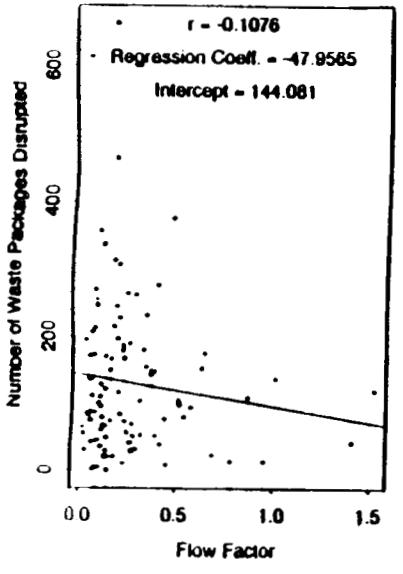
Parameter No. 11



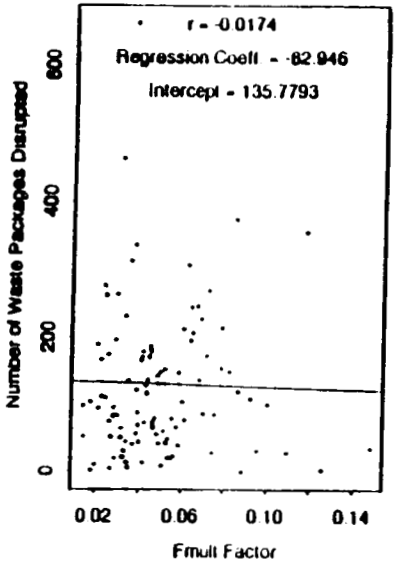
Parameter No. 12



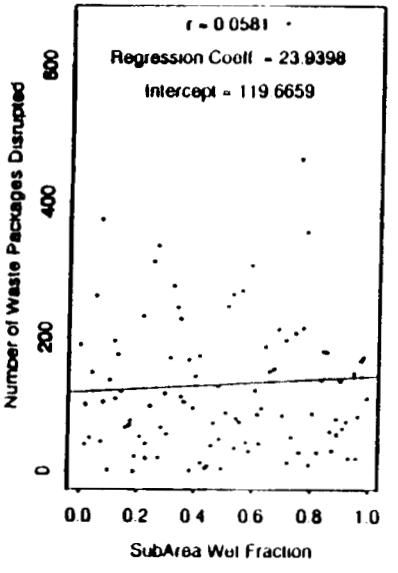
Parameter No. 13



Parameter No. 14



Parameter No. 15



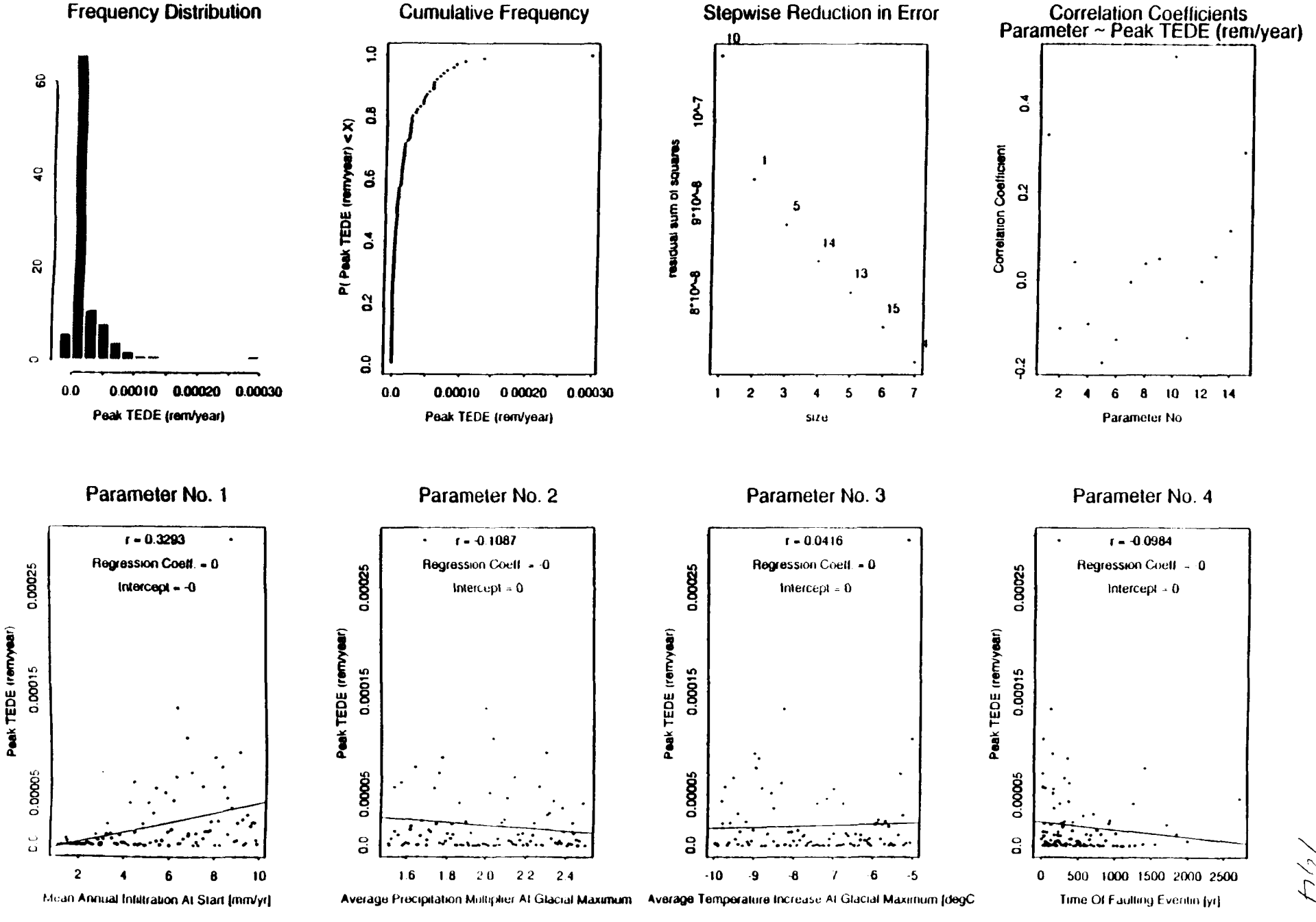
76/94

APPENDIX J

Run: FLTO_Run9

Distance to Critical Group = 20 km
Recurrence Interval = 500 yr
Only FAULTO, Uniform Corrosion, Backfill

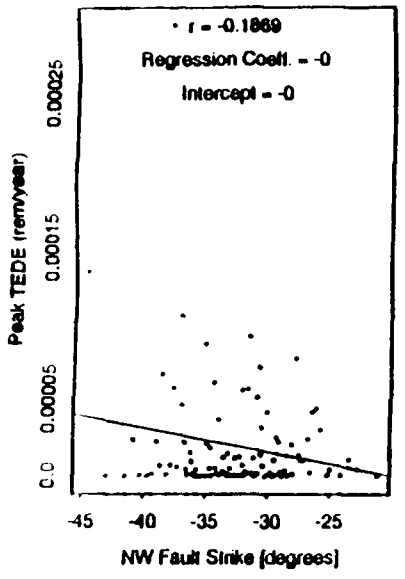
20 km Scenario
Summary Plots for Peak TEDE (rem/year)



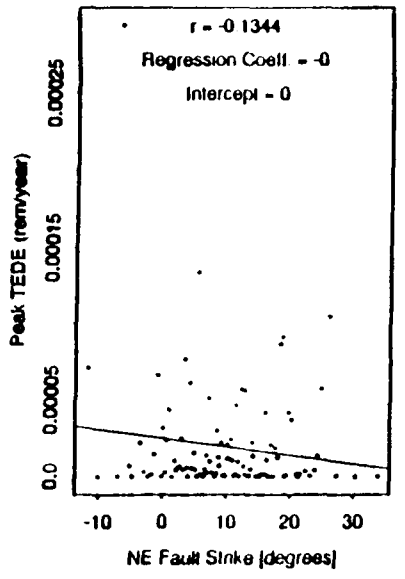
J-1

78/94

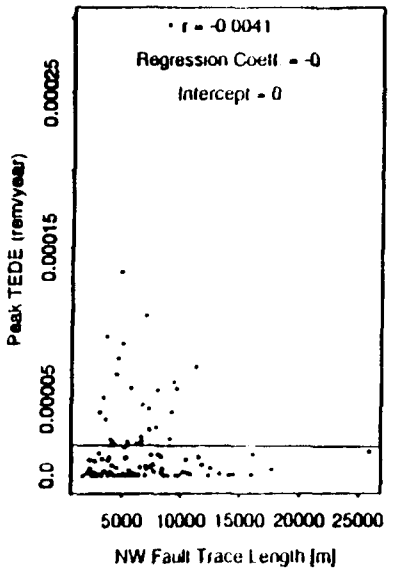
Parameter No. 5



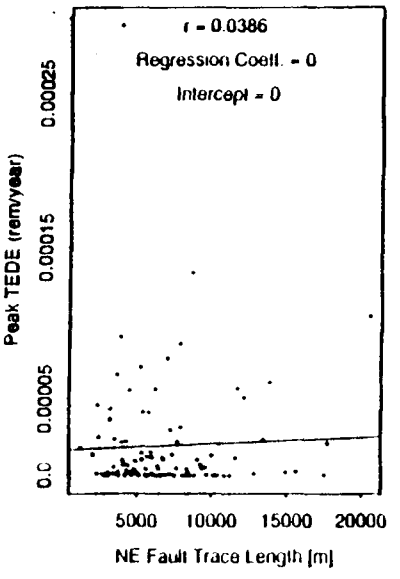
Parameter No. 6



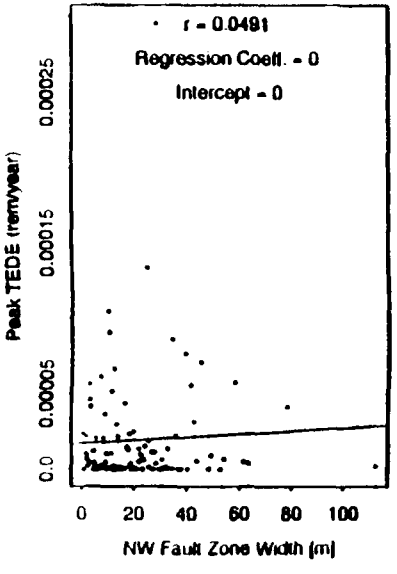
Parameter No. 7



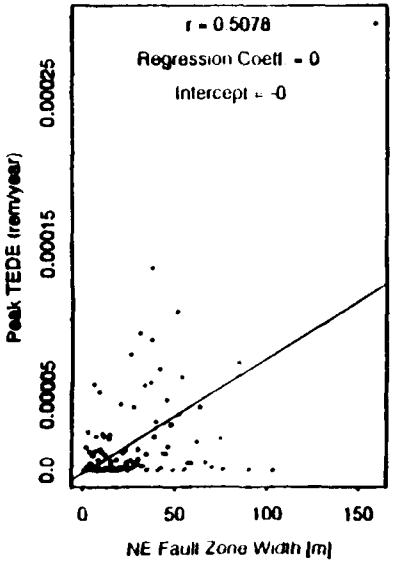
Parameter No. 8



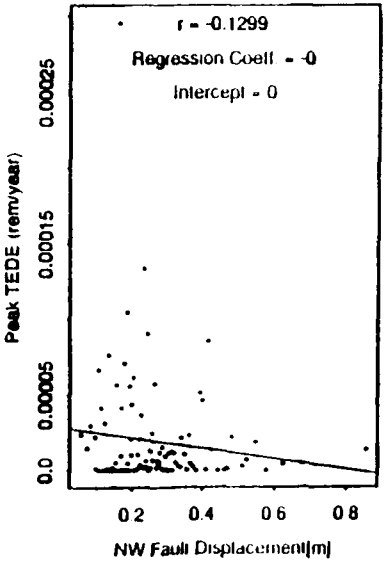
Parameter No. 9



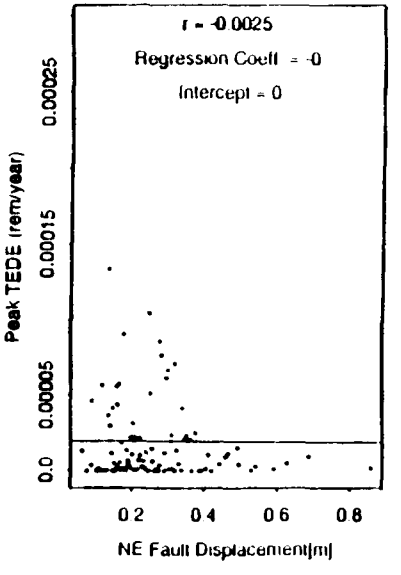
Parameter No. 10



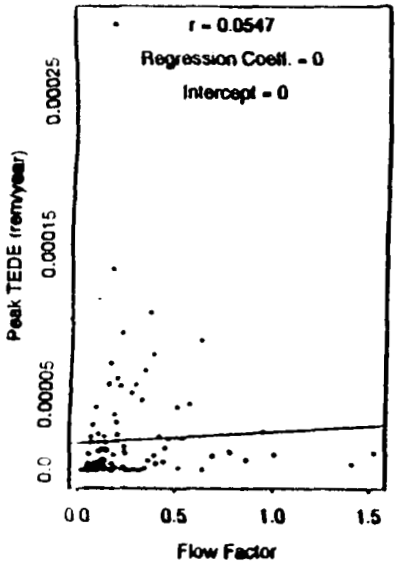
Parameter No. 11



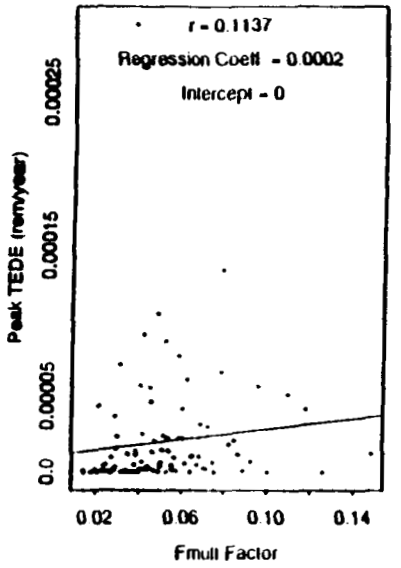
Parameter No. 12



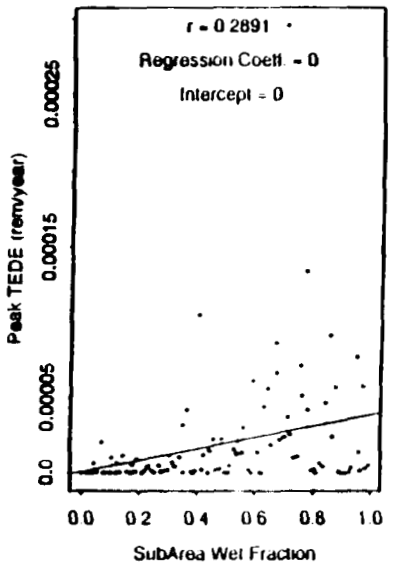
Parameter No. 13



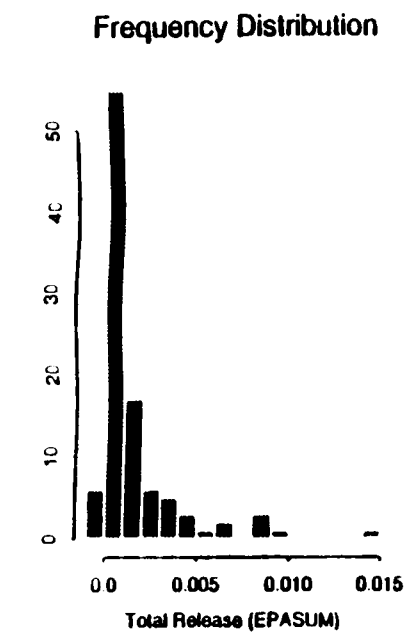
Parameter No. 14

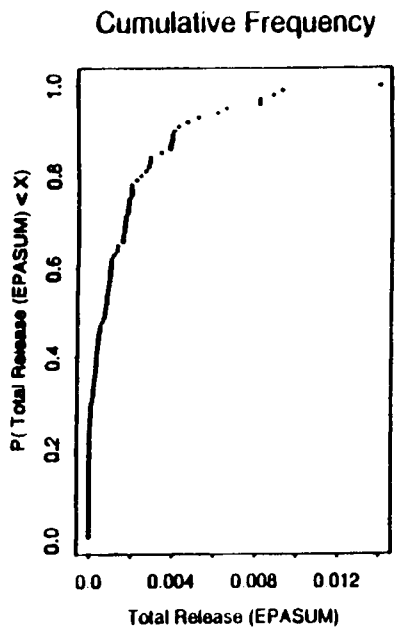


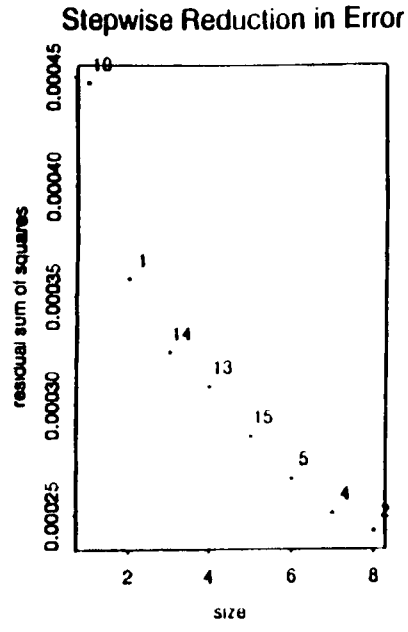
Parameter No. 15

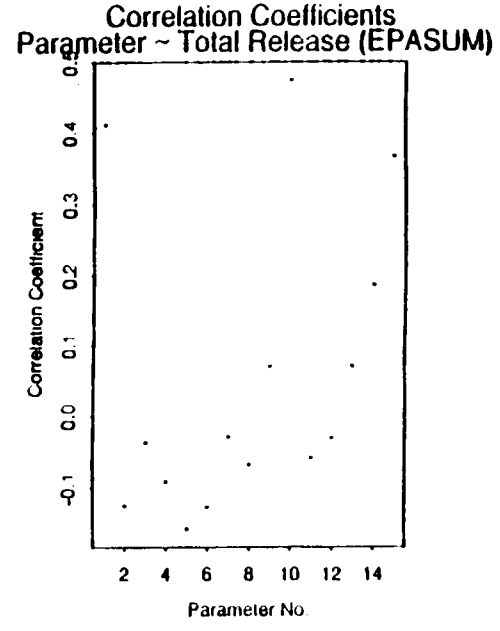


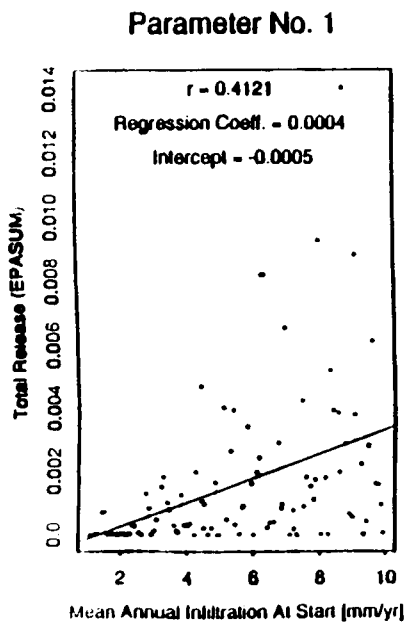
20 km Scenario
Summary Plots for Total Release (EPASUM)

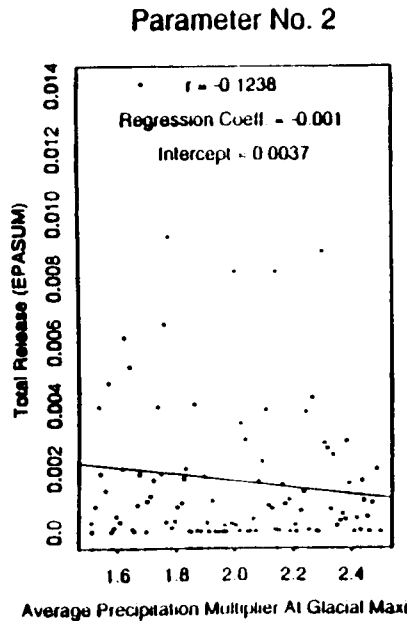


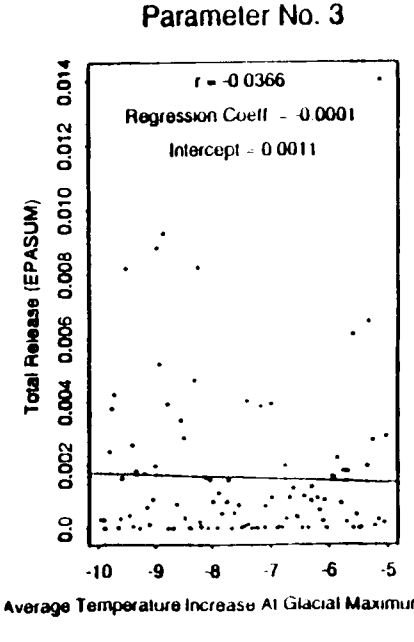


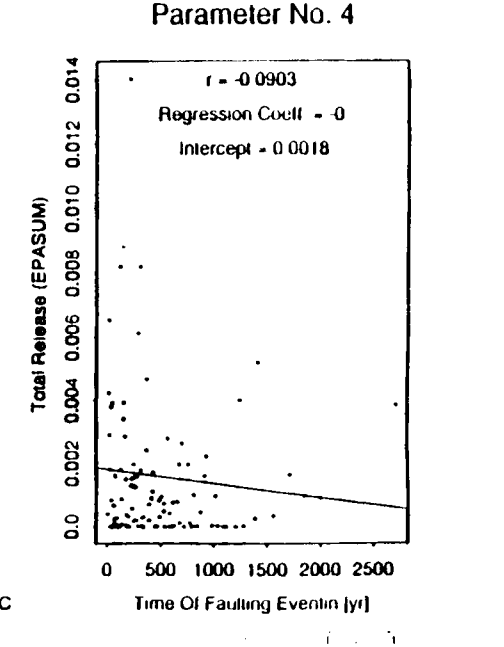




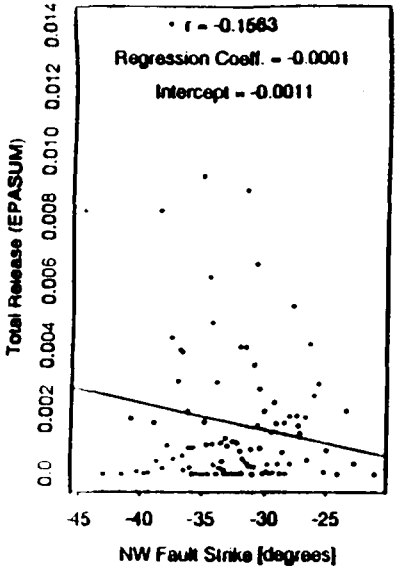




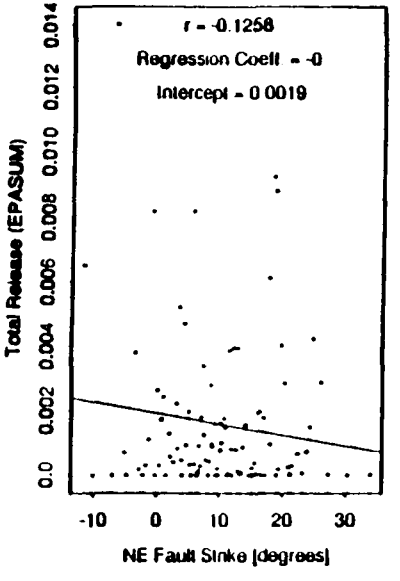




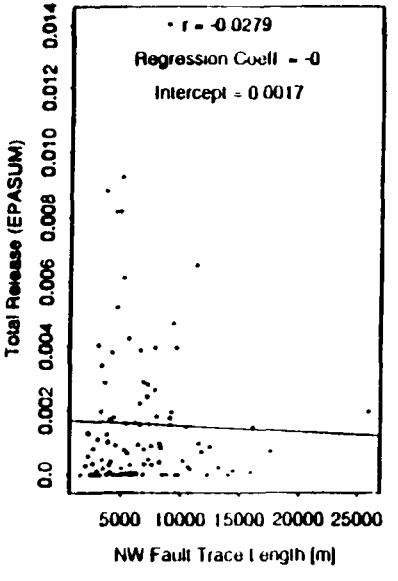
Parameter No. 5



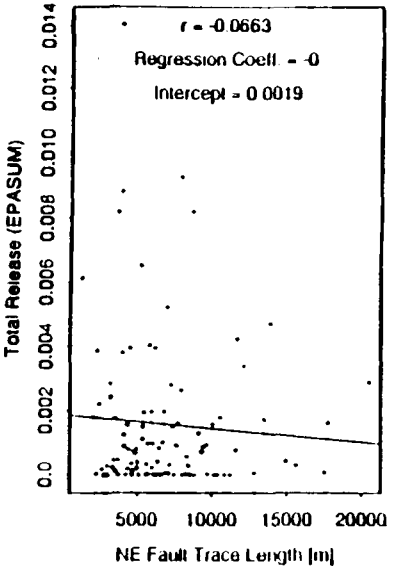
Parameter No. 6



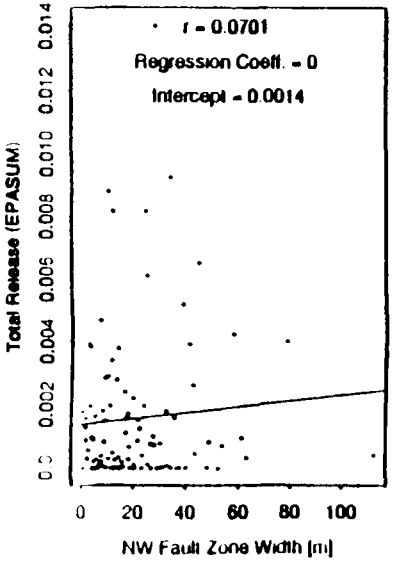
Parameter No. 7



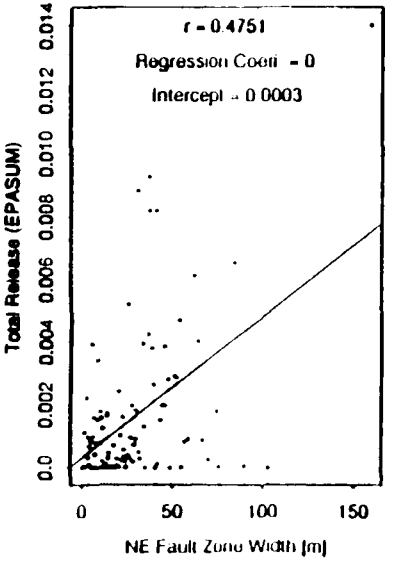
Parameter No. 8



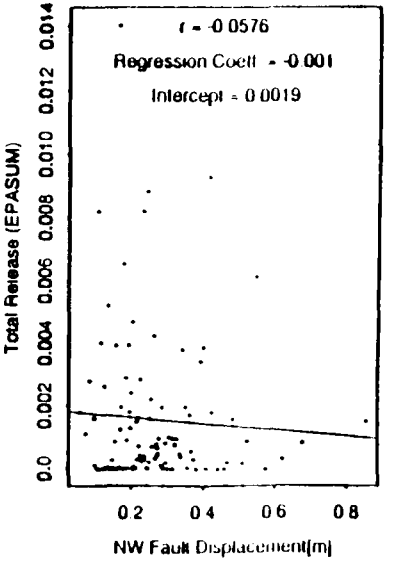
Parameter No. 9



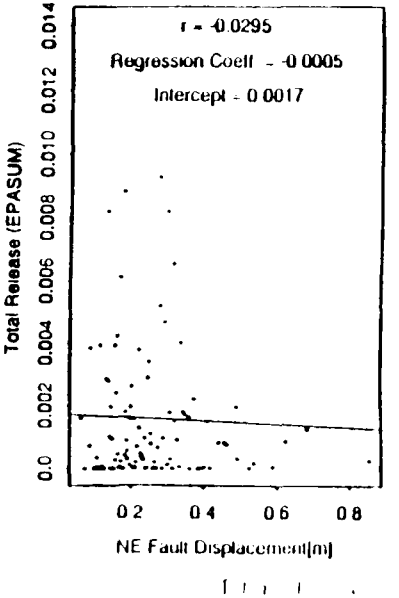
Parameter No. 10



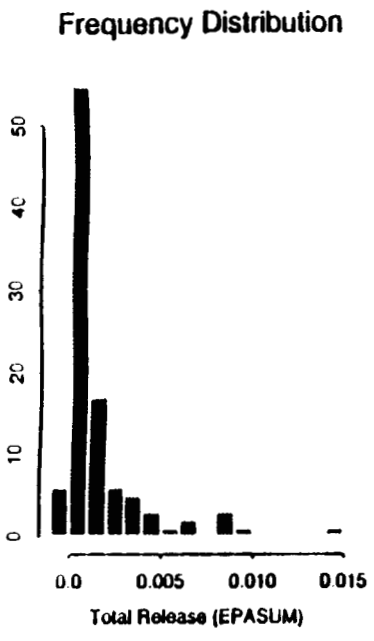
Parameter No. 11

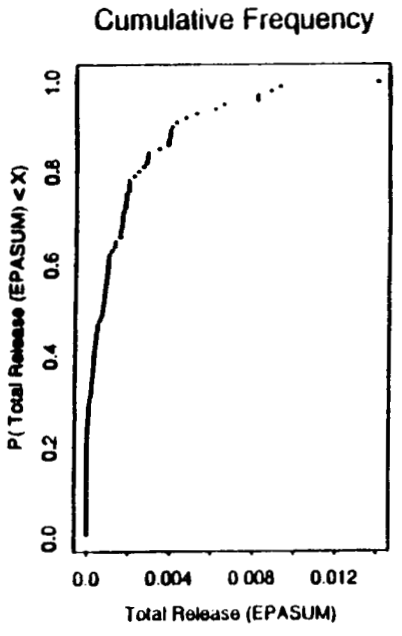


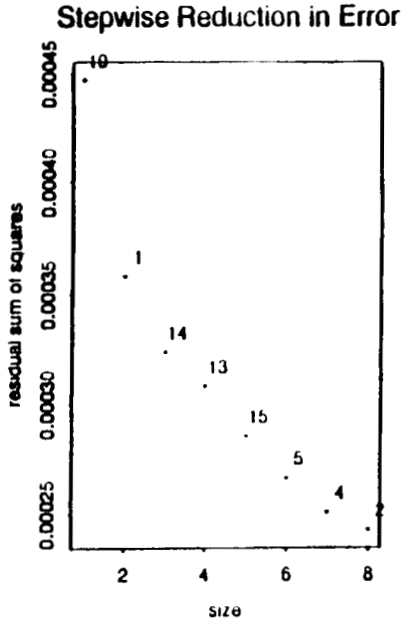
Parameter No. 12

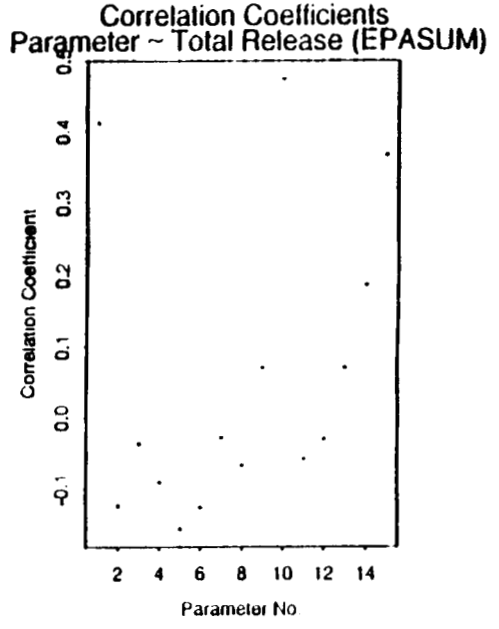


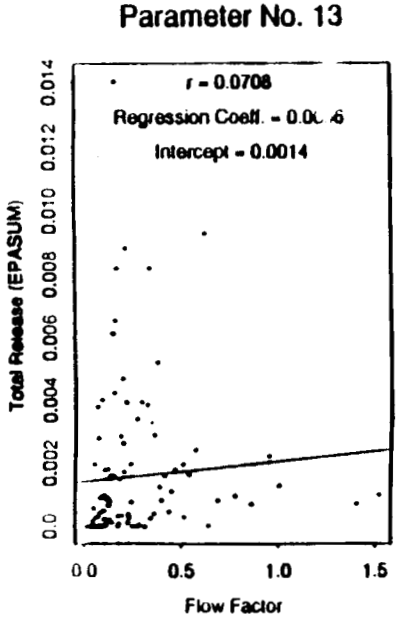
20 km Scenario
Summary Plots for Total Release (EPASUM)

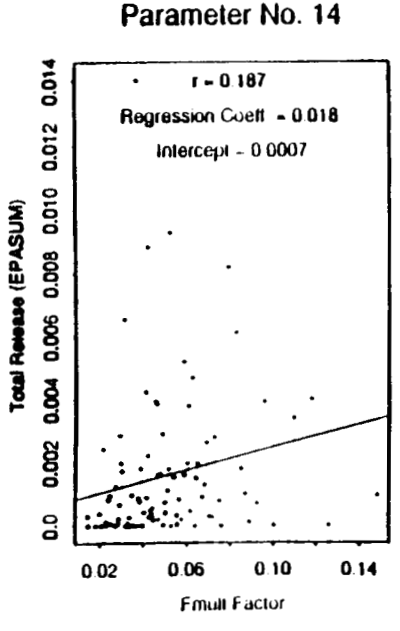


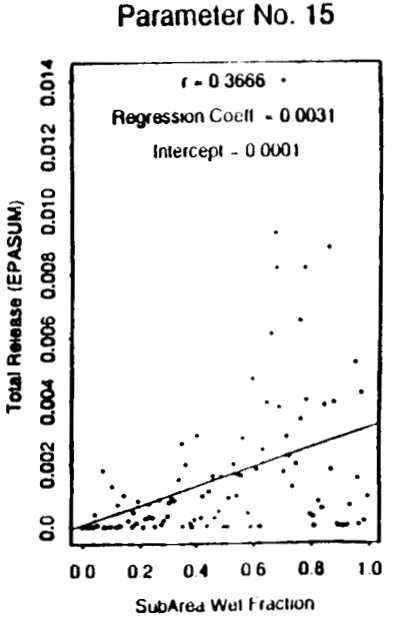




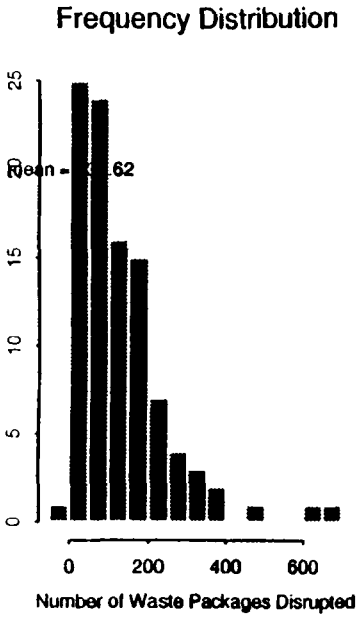


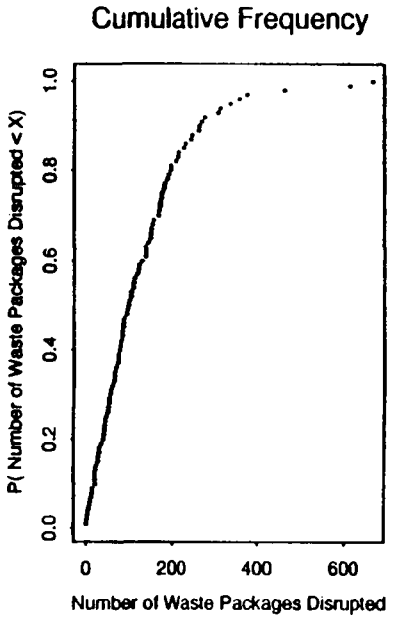


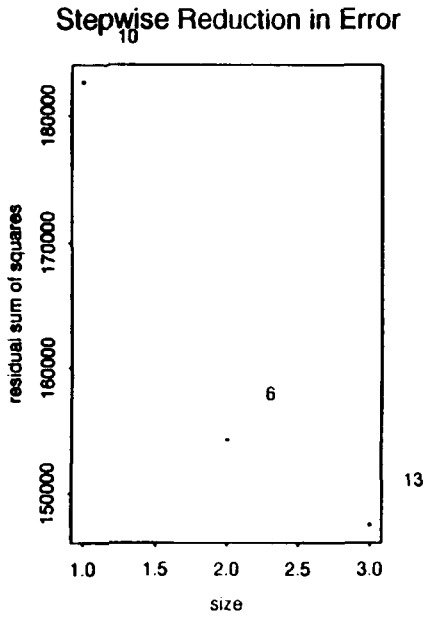


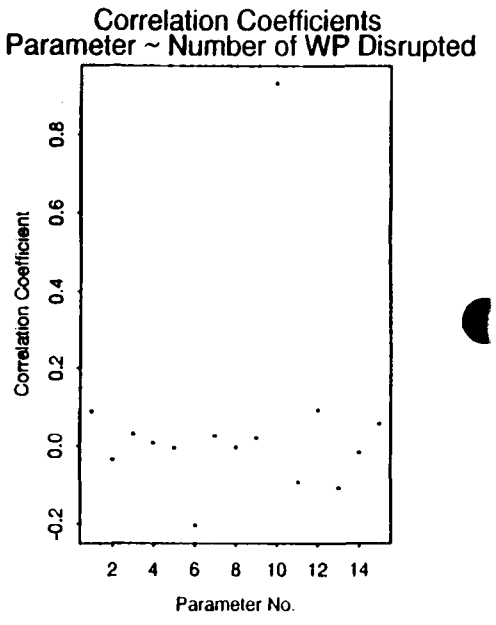


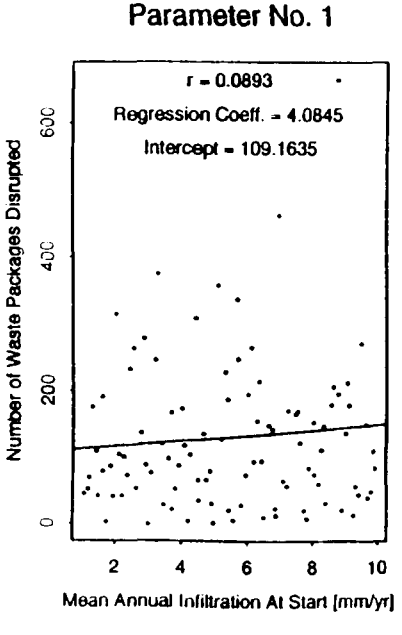
20 km Scenario
Summary Plots for Number of Waste Packages Disrupted

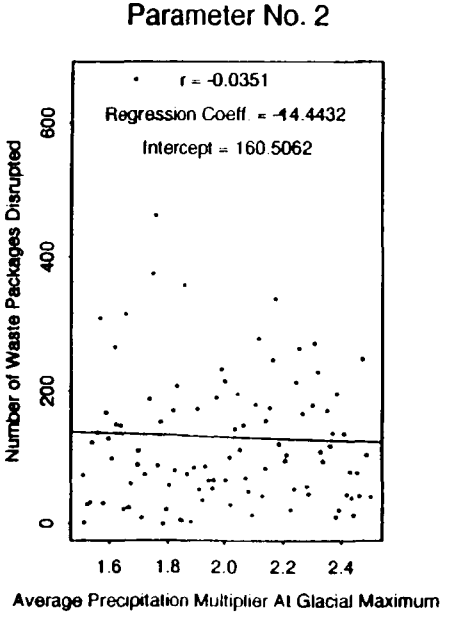


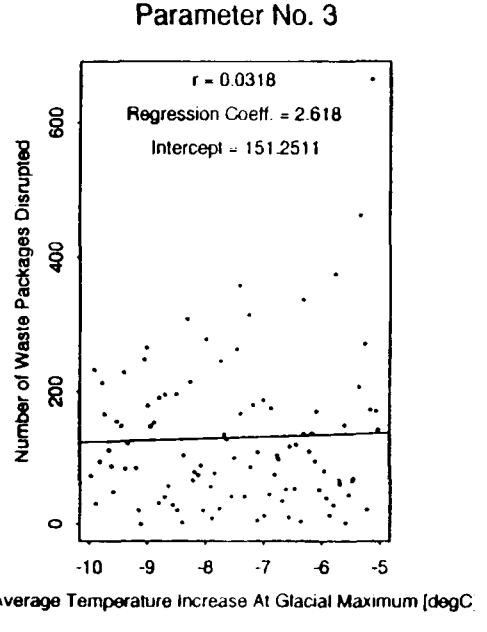


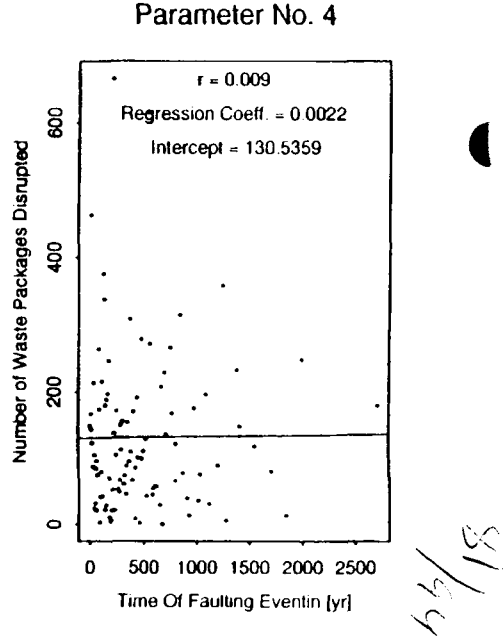




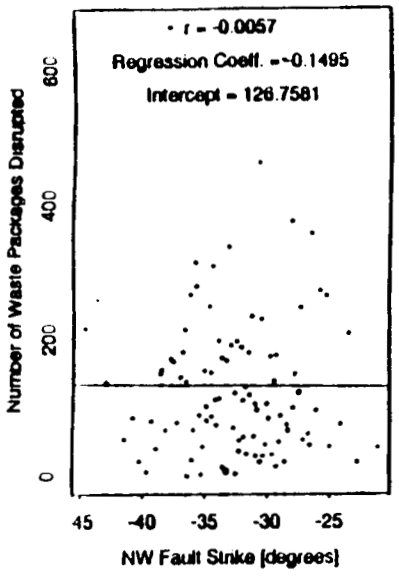




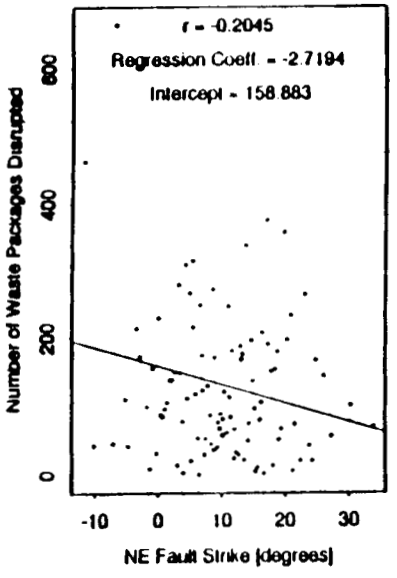




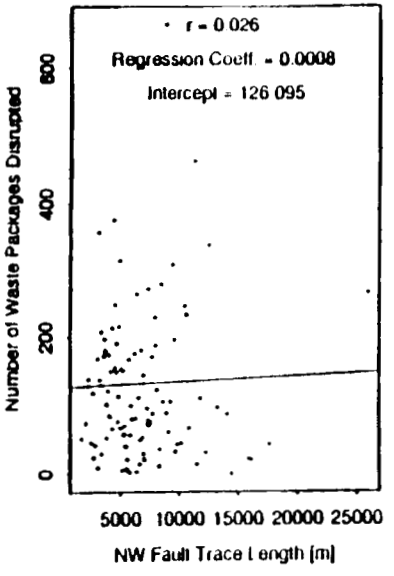
Parameter No. 5



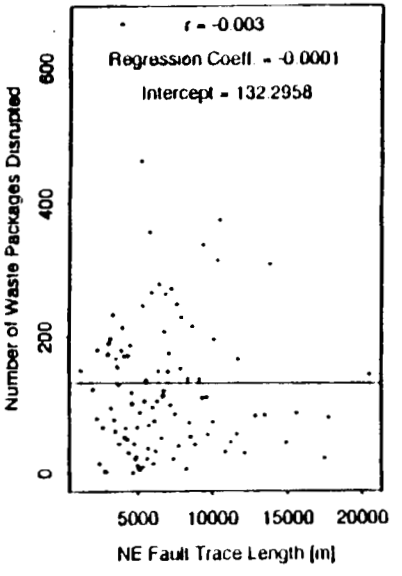
Parameter No. 6



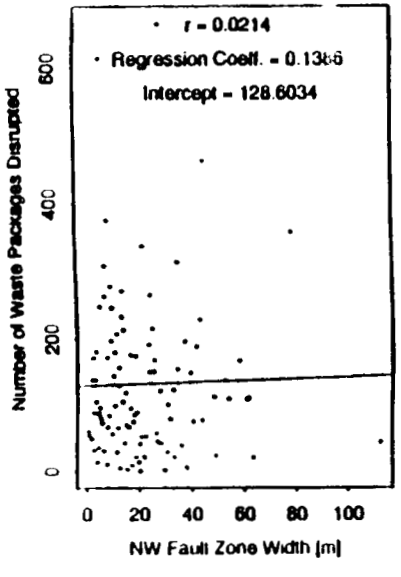
Parameter No. 7



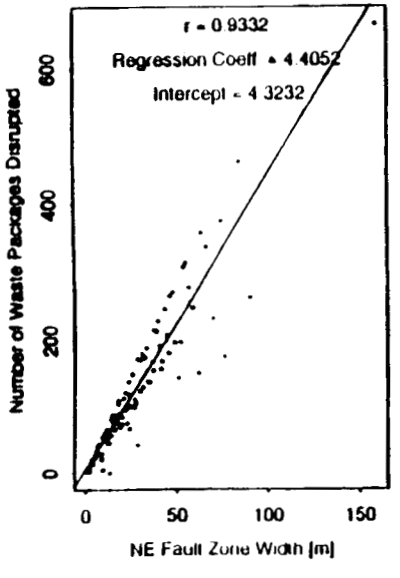
Parameter No. 8



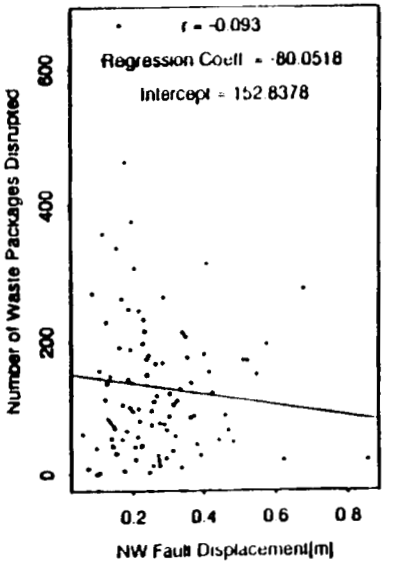
Parameter No. 9



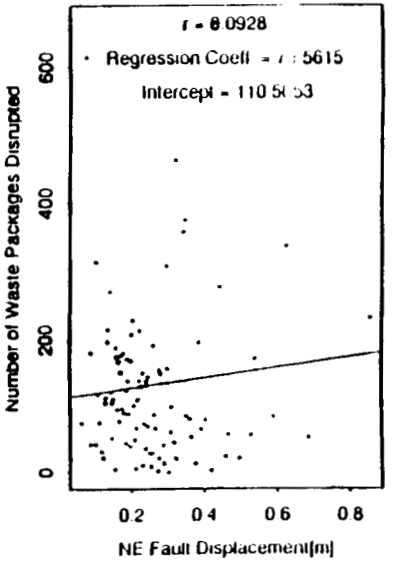
Parameter No. 10



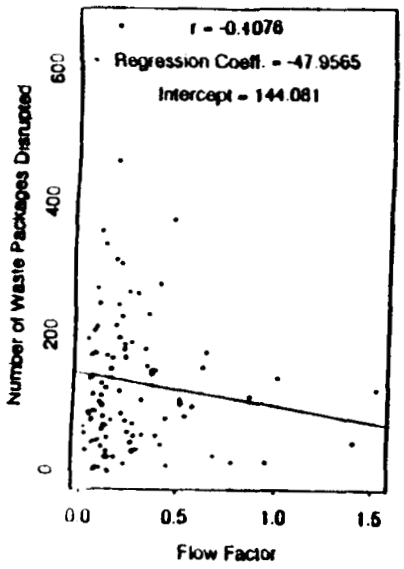
Parameter No. 11



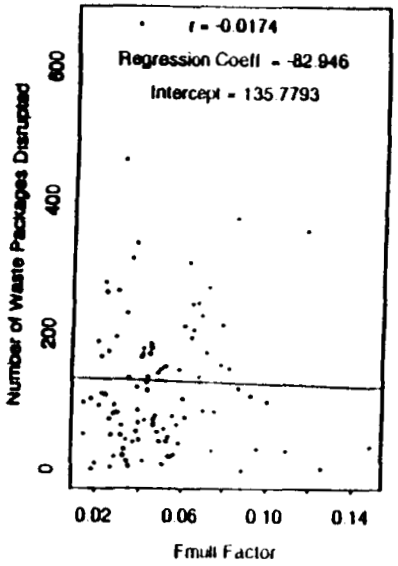
Parameter No. 12



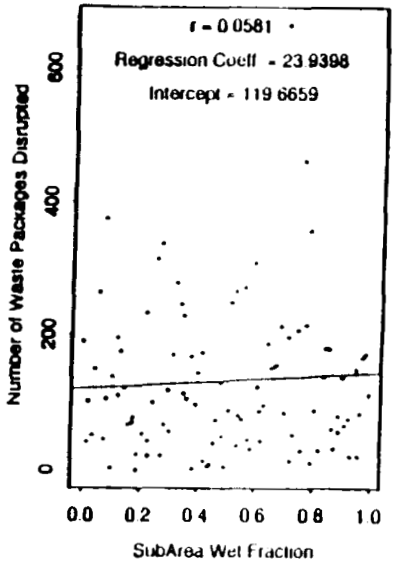
Parameter No. 13



Parameter No. 14



Parameter No. 15



83/94

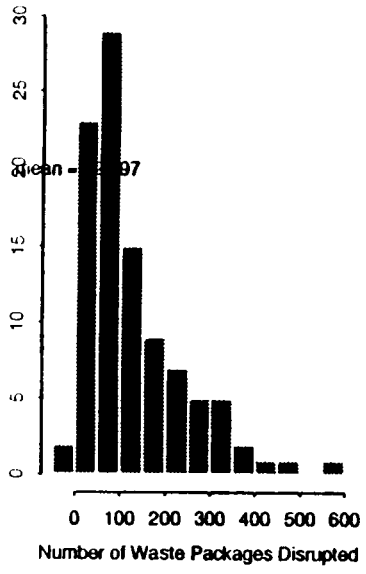
APPENDIX K

Run: FLTO_Run10

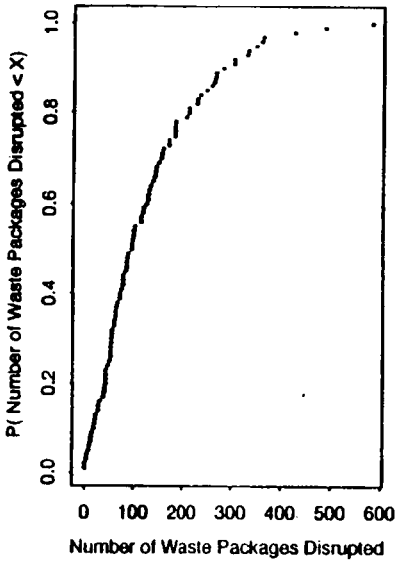
Distance to Critical Group = 5 km
Recurrence Interval = 5,000 yr
Only FAULTO, Uniform Corrosion, No Backfill

5 km Scenario
Summary Plots for Number of Waste Packages Disrupted

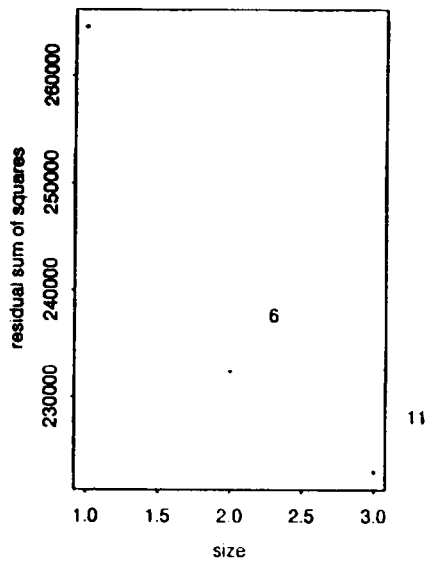
Frequency Distribution



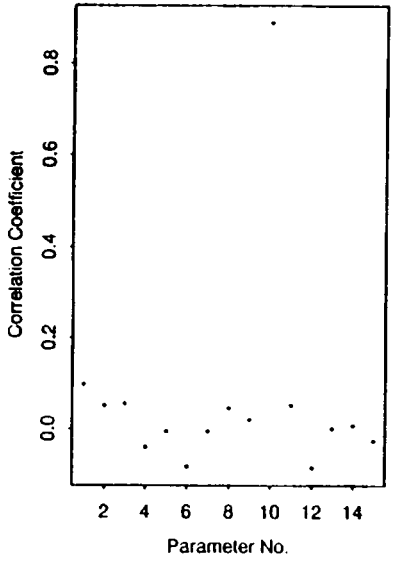
Cumulative Frequency



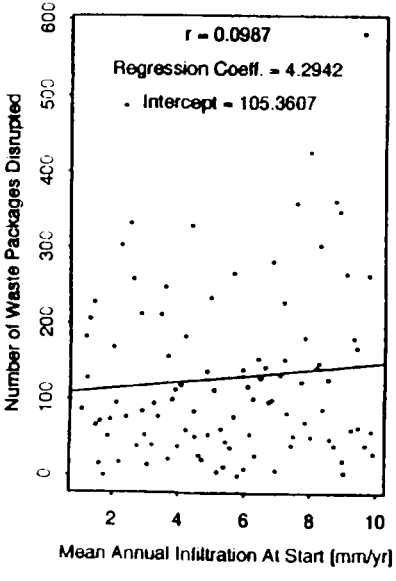
Stepwise Reduction in Error



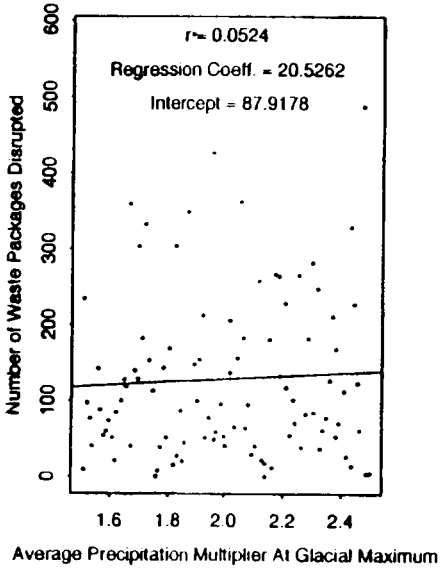
Correlation Coefficients
Parameter ~ Number of WP Disrupted



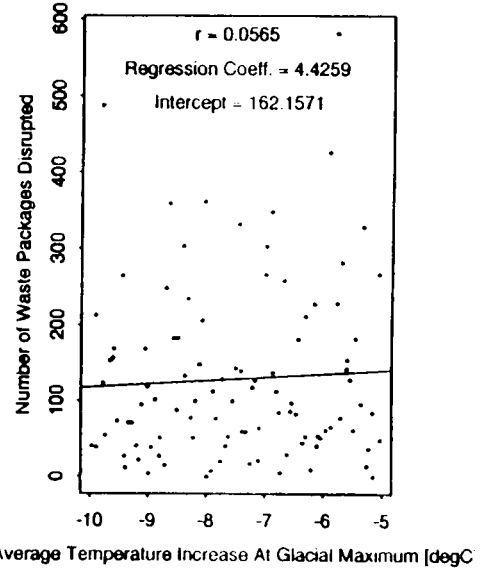
Parameter No. 1



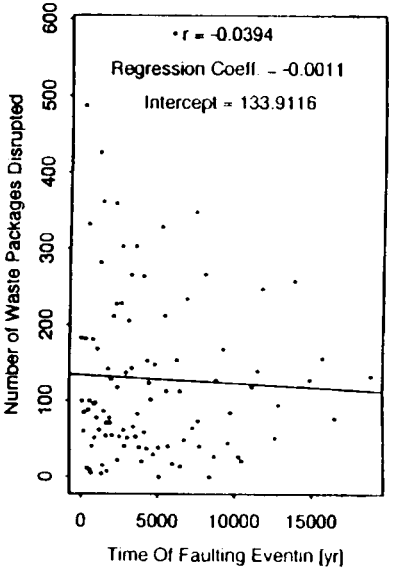
Parameter No. 2



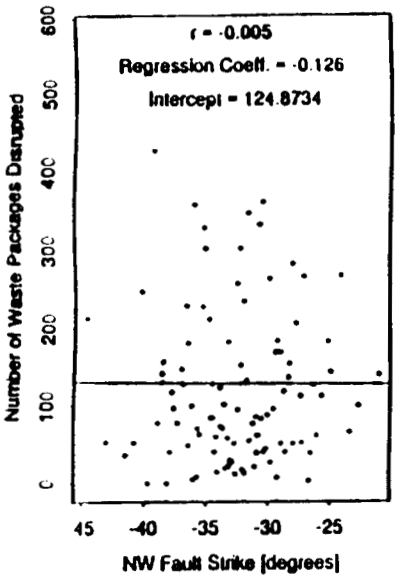
Parameter No. 3



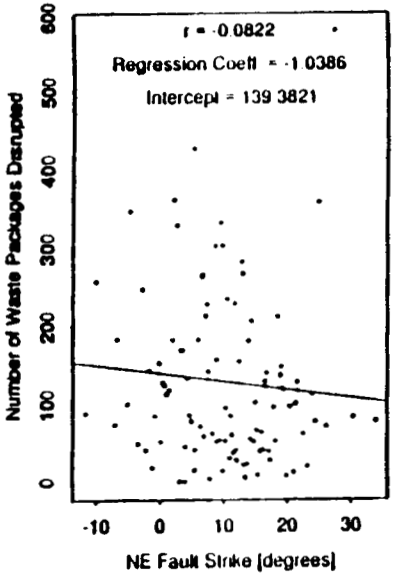
Parameter No. 4



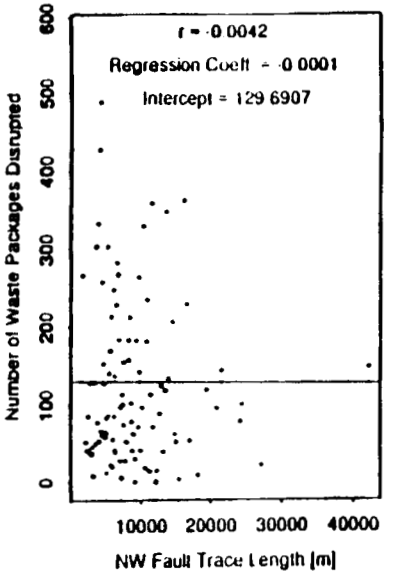
Parameter No. 5



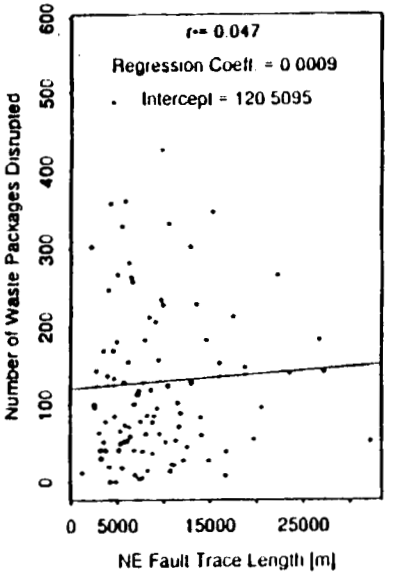
Parameter No. 6



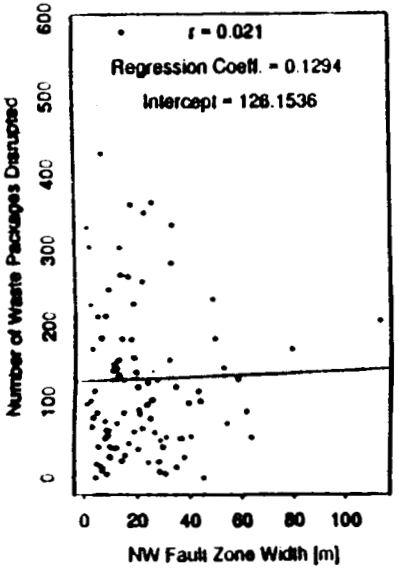
Parameter No. 7



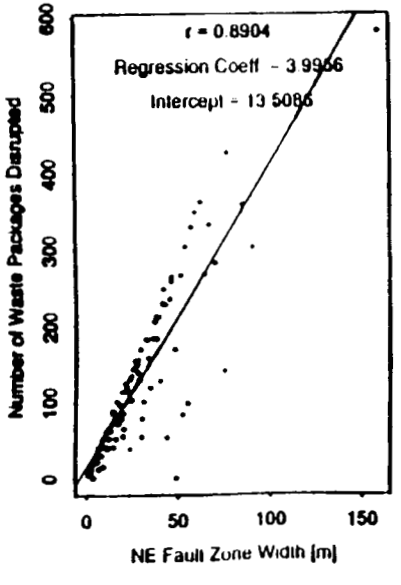
Parameter No. 8



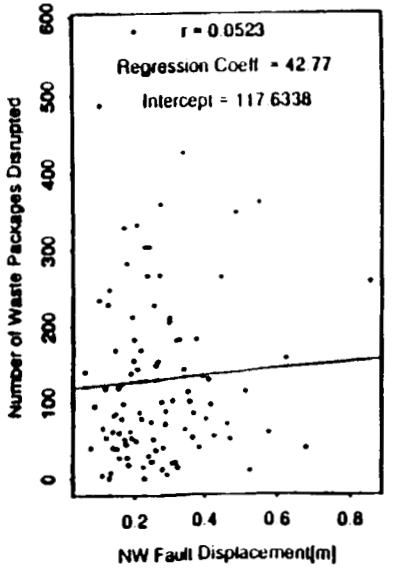
Parameter No. 9



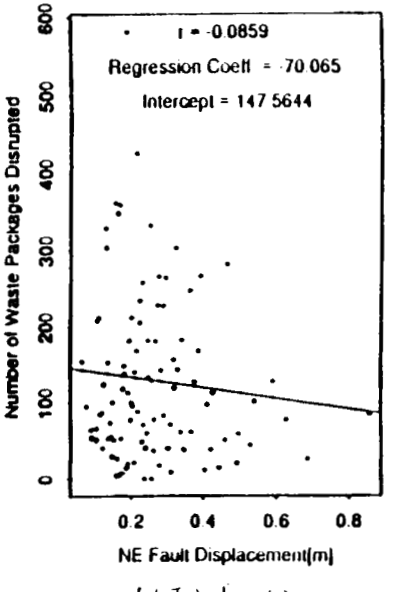
Parameter No. 10



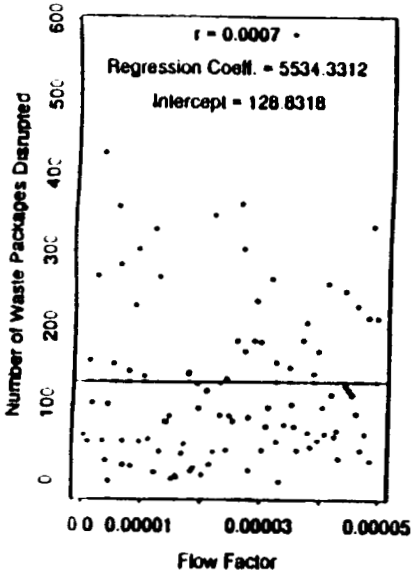
Parameter No. 11



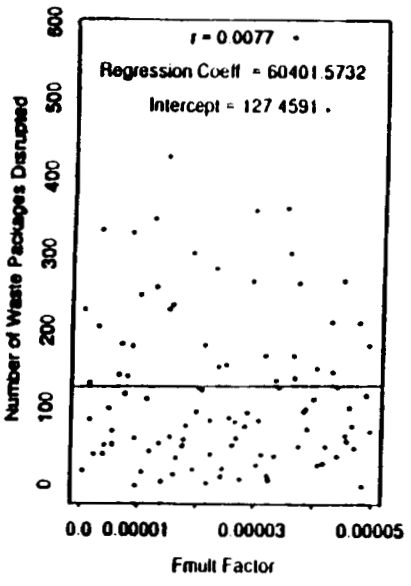
Parameter No. 12



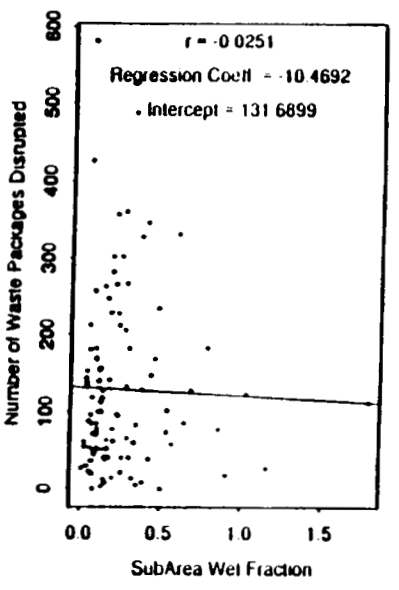
Parameter No. 13



Parameter No. 14

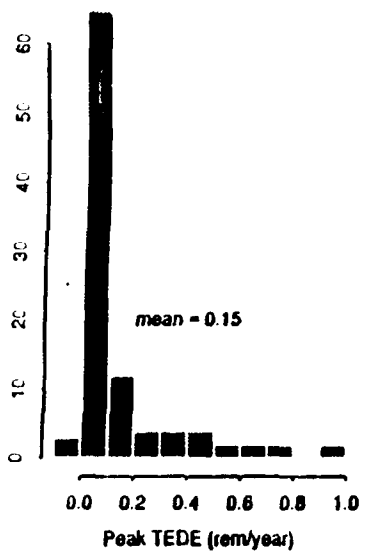


Parameter No. 15

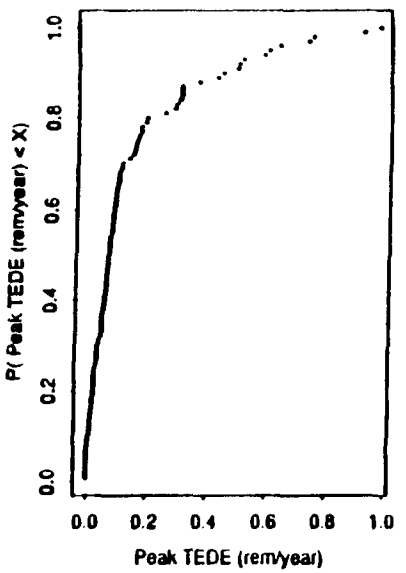


5 km Scenario
Summary Plots for Peak TEDE (rem/year)

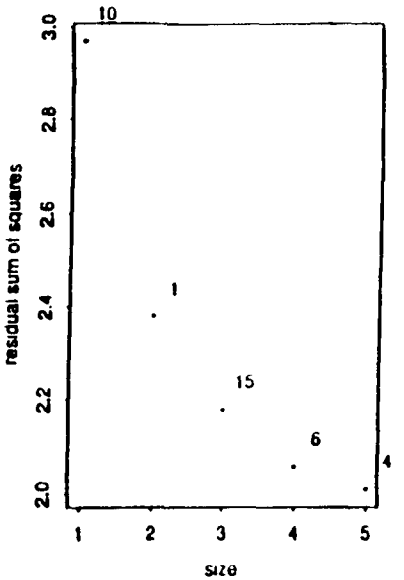
Frequency Distribution



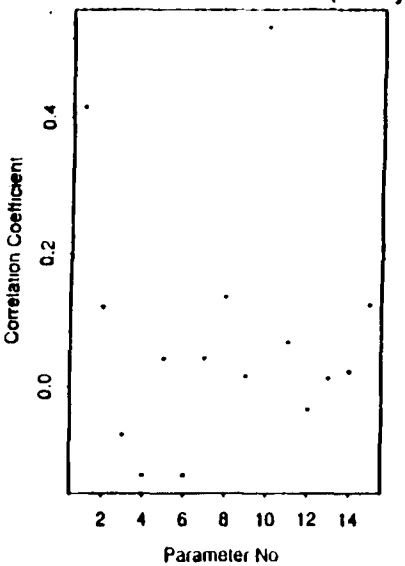
Cumulative Frequency



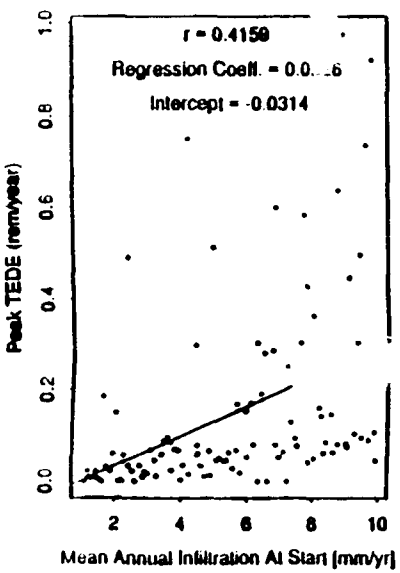
Stepwise Reduction in Error



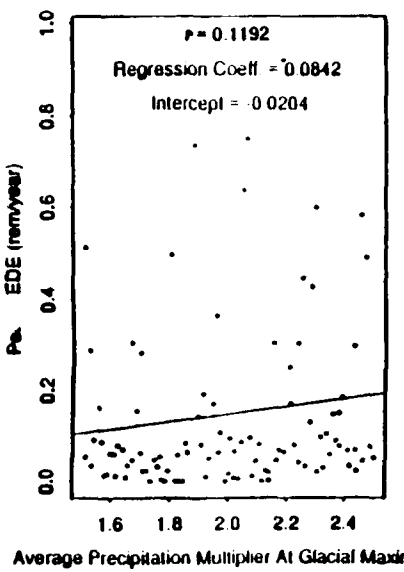
Correlation Coefficients
Parameter ~ Peak TEDE (rem/year)



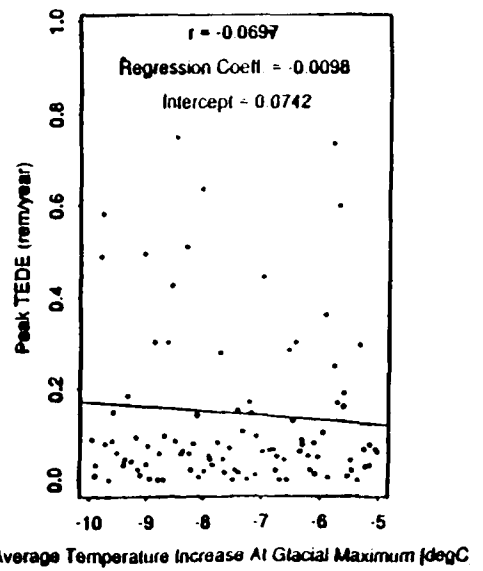
Parameter No. 1



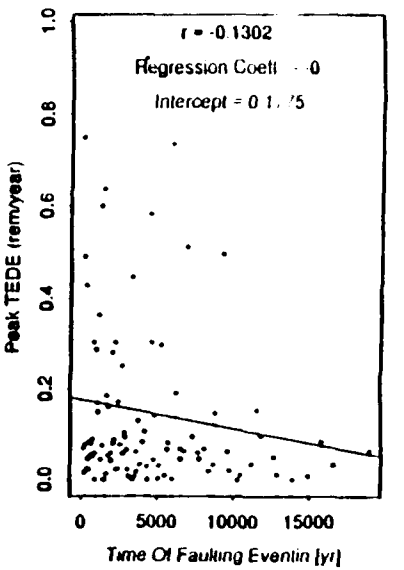
Parameter No. 2



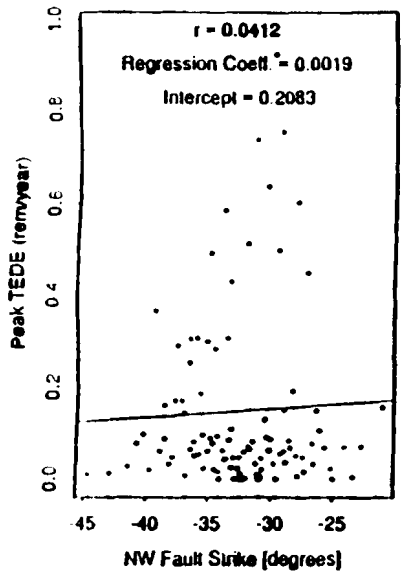
Parameter No. 3



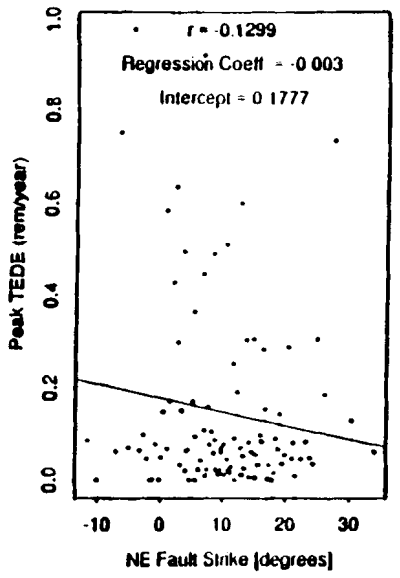
Parameter No. 4



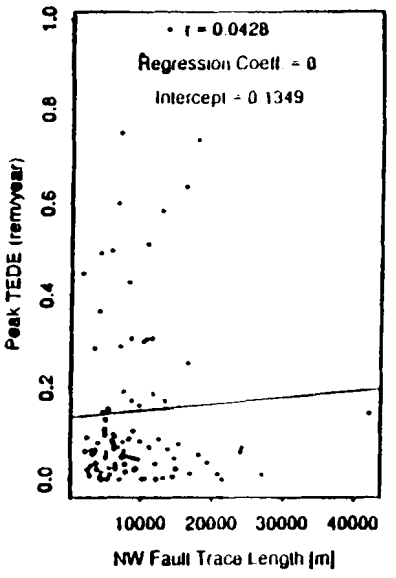
Parameter No. 5



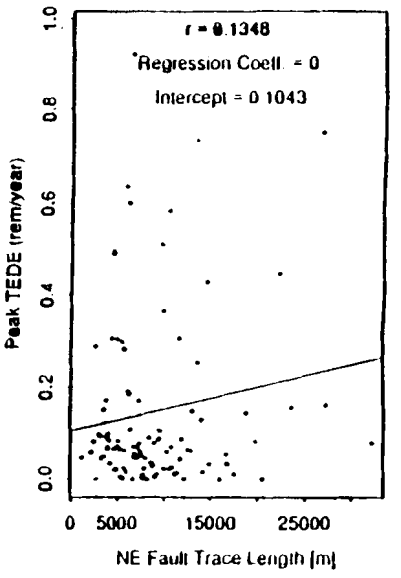
Parameter No. 6



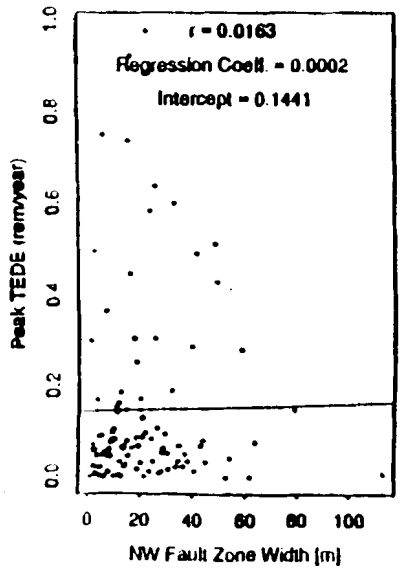
Parameter No. 7



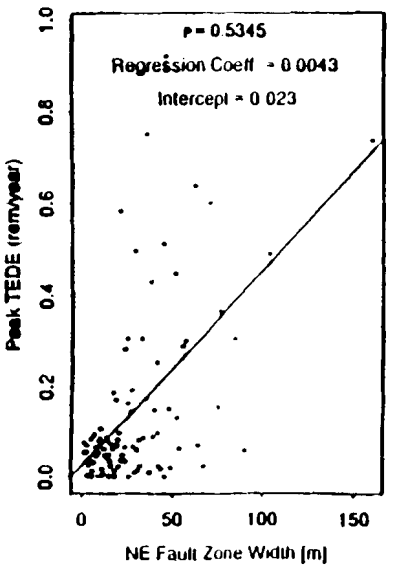
Parameter No. 8



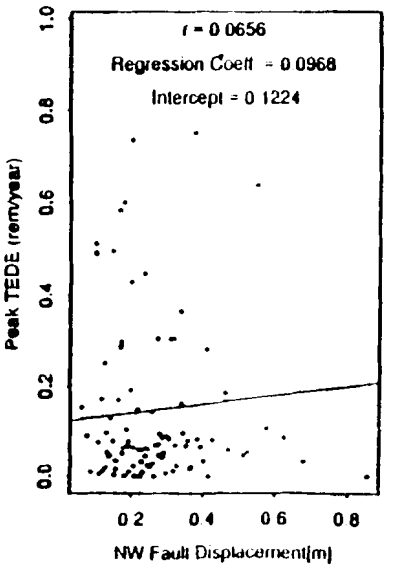
Parameter No. 9



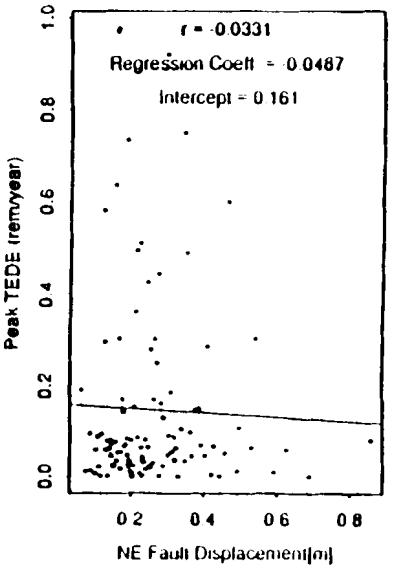
Parameter No. 10



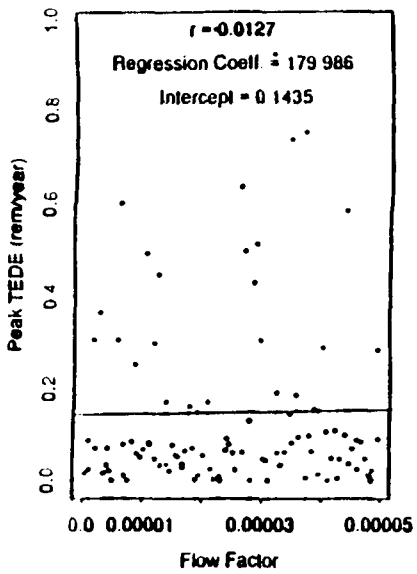
Parameter No. 11



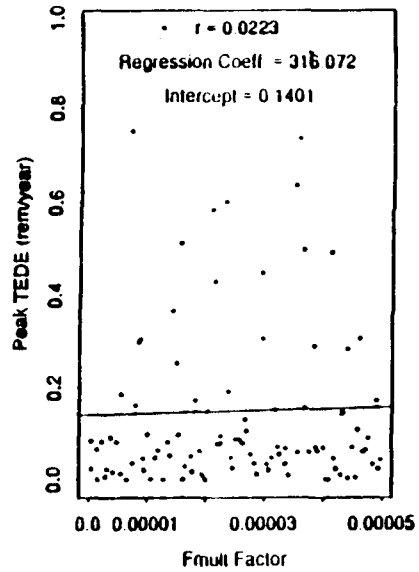
Parameter No. 12



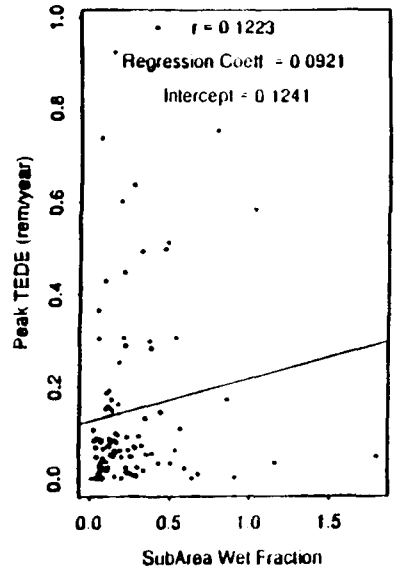
Parameter No. 13



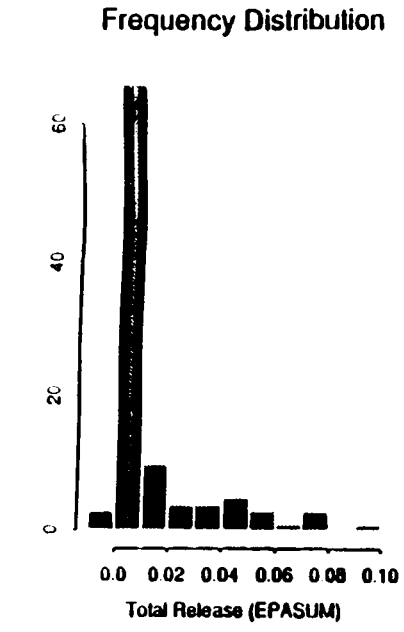
Parameter No. 14

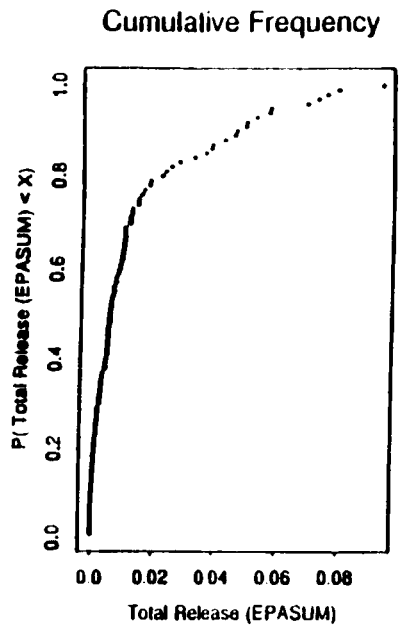


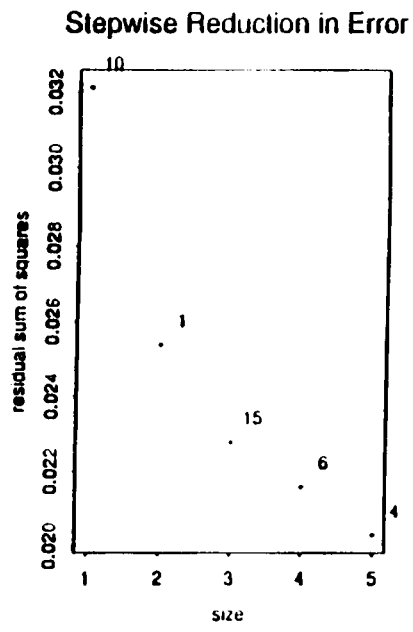
Parameter No. 15

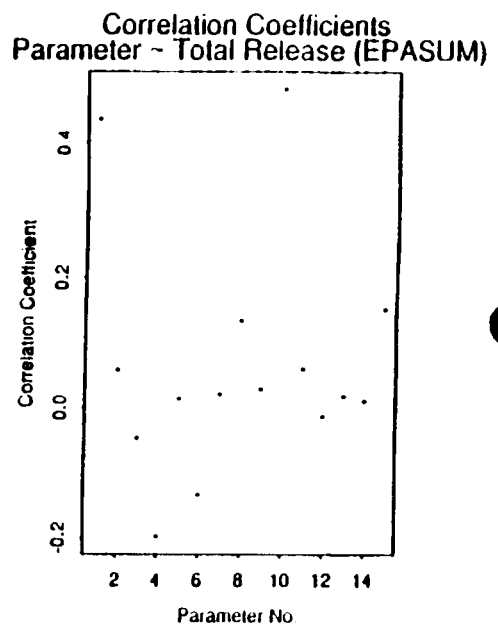


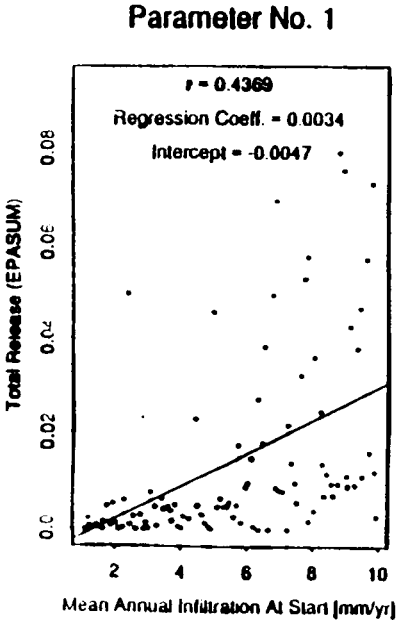
5 km Scenario
Summary Plots for Total Release (EPASUM)

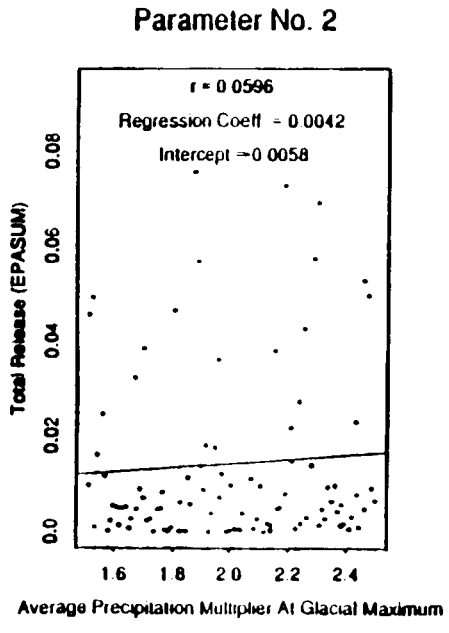


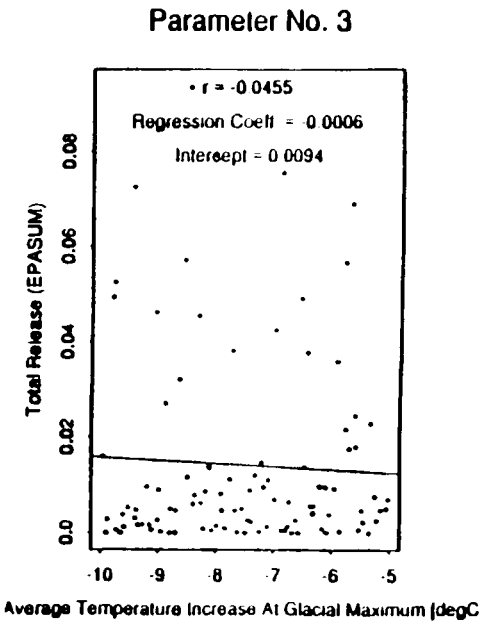


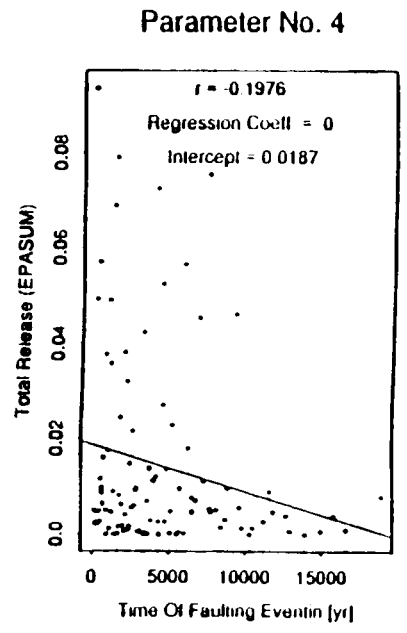




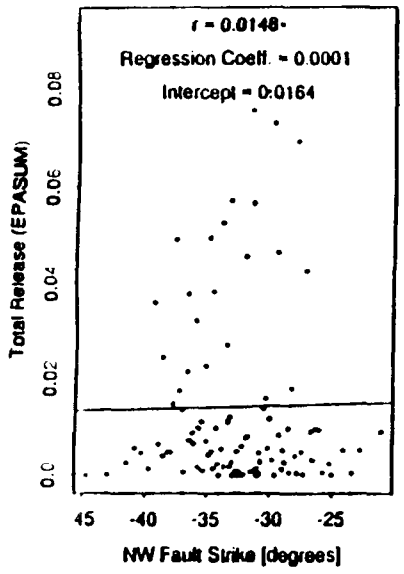




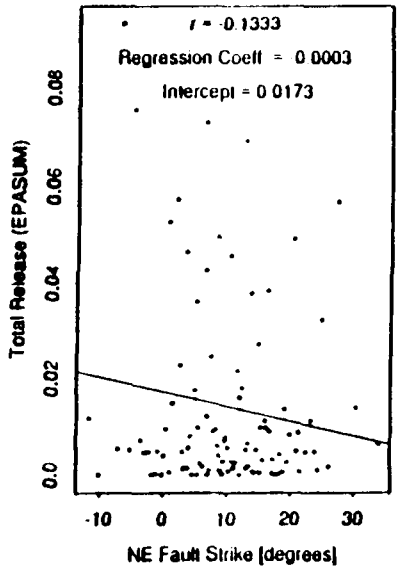




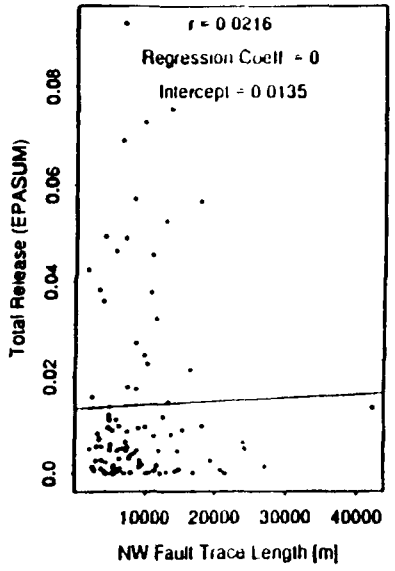
Parameter No. 5



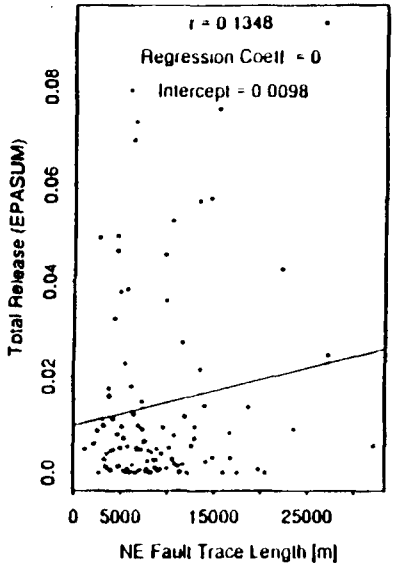
Parameter No. 6



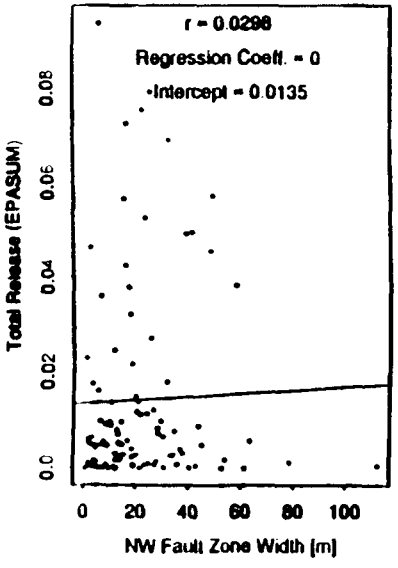
Parameter No. 7



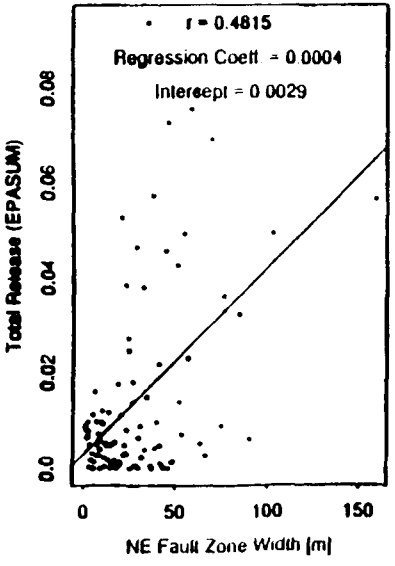
Parameter No. 8



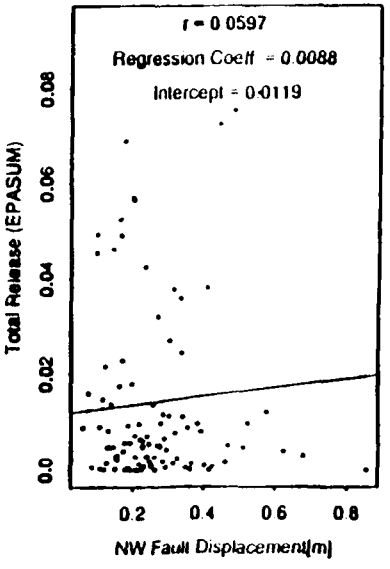
Parameter No. 9



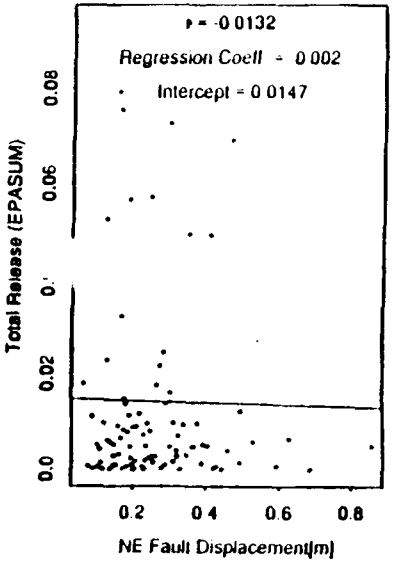
Parameter No. 10



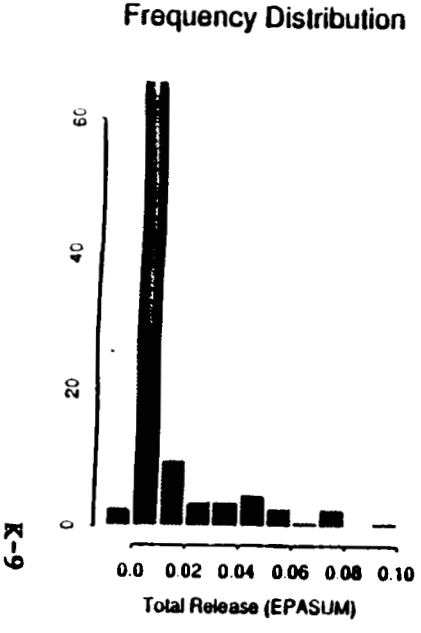
Parameter No. 11

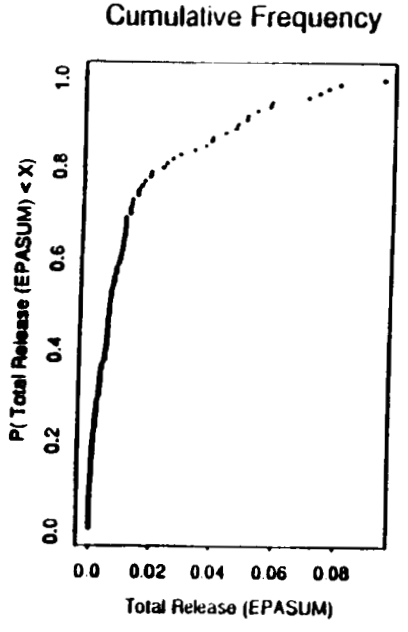


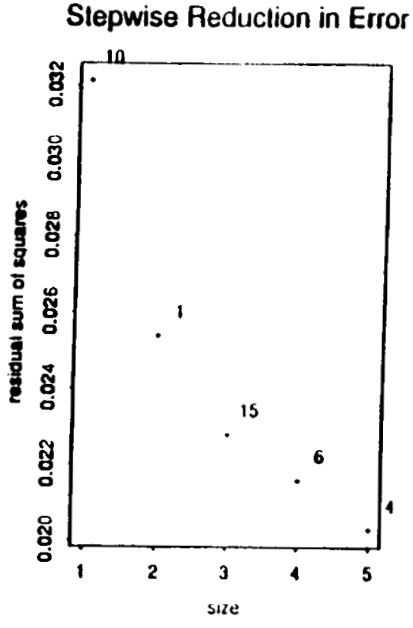
Parameter No. 12

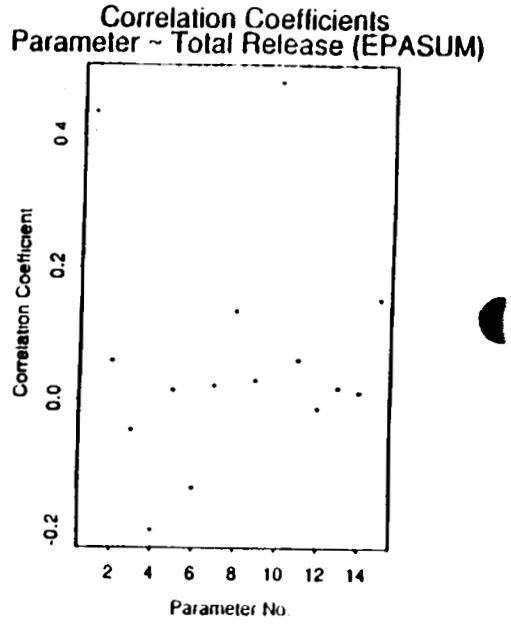


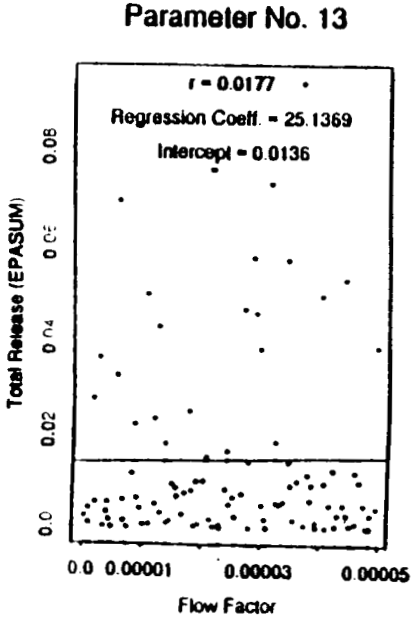
5 km Scenario
Summary Plots for Total Release (EPASUM)

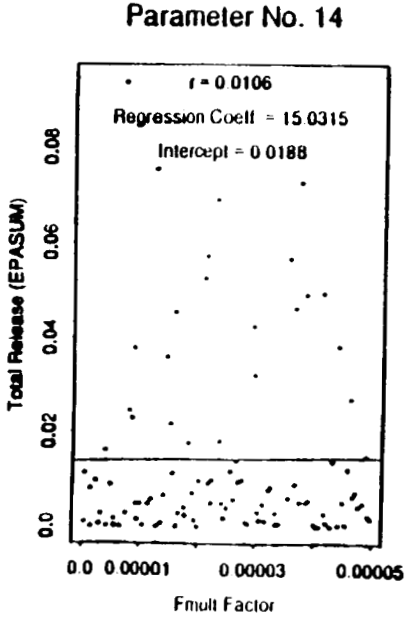


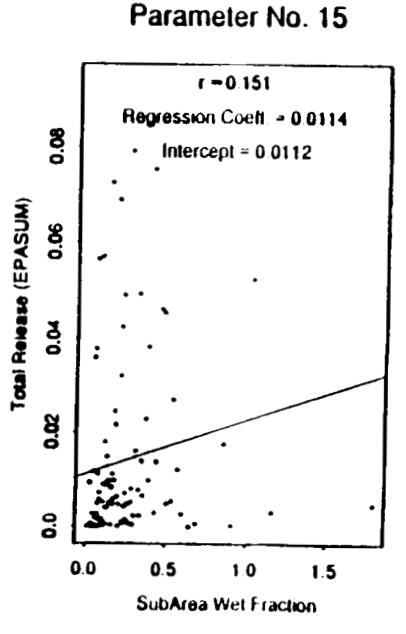












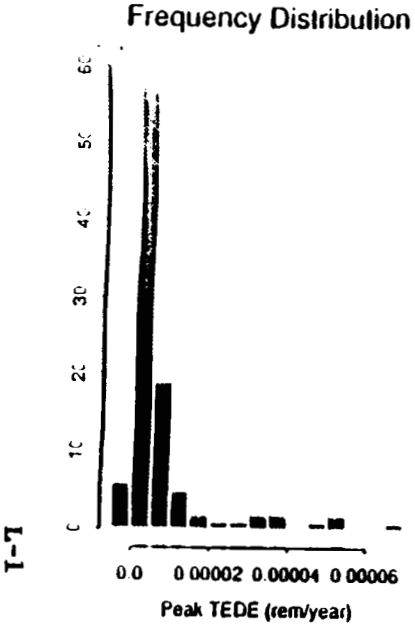
89/94

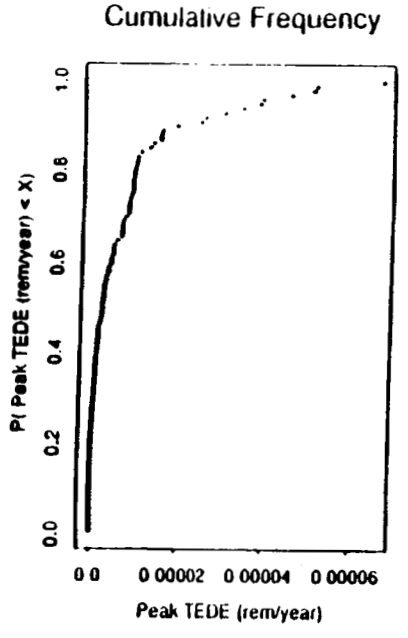
APPENDIX L

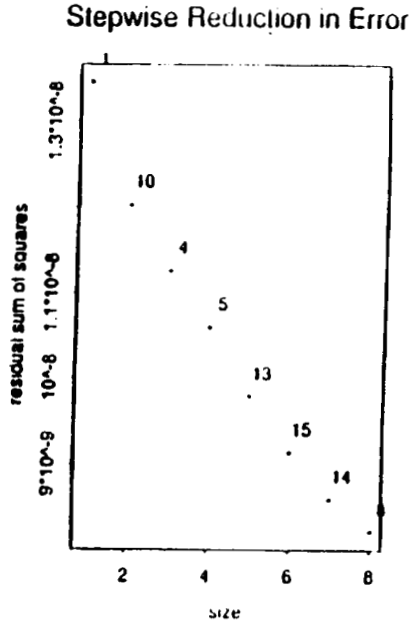
Run: FLTO_Run11

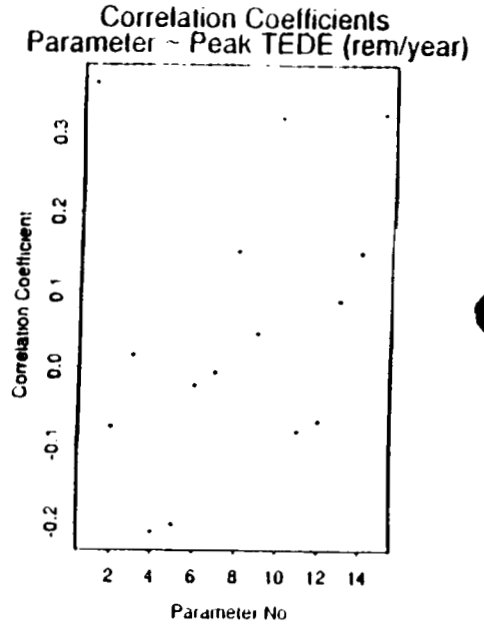
Distance to Critical Group = 20 km
Recurrence Interval = 5,000 yr
Only FAULTO, Uniform Corrosion, No Backfill

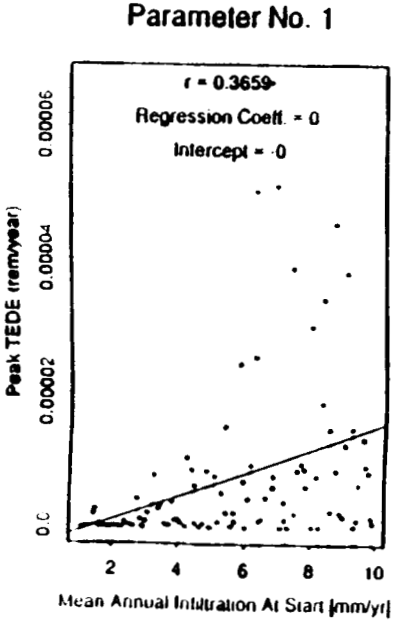
20 km Scenario
Summary Plots for Peak TEDE (rem/year)

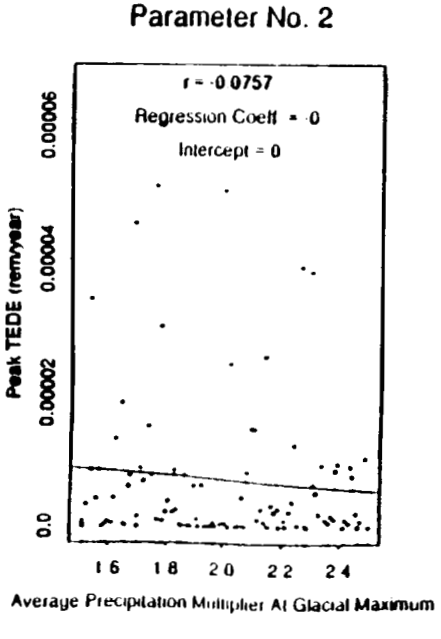


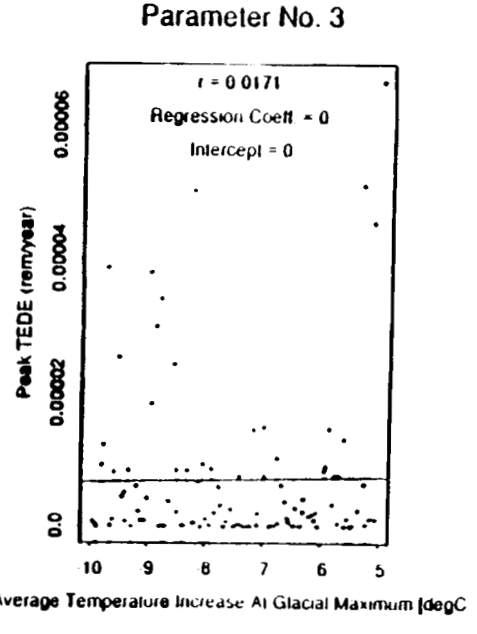


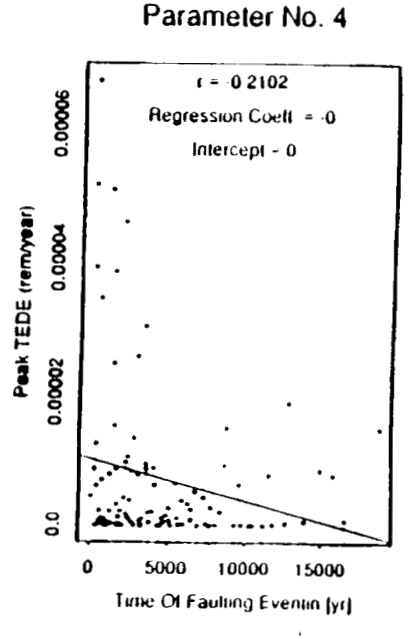




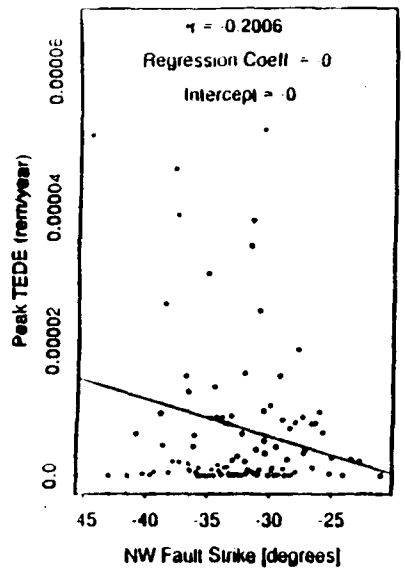




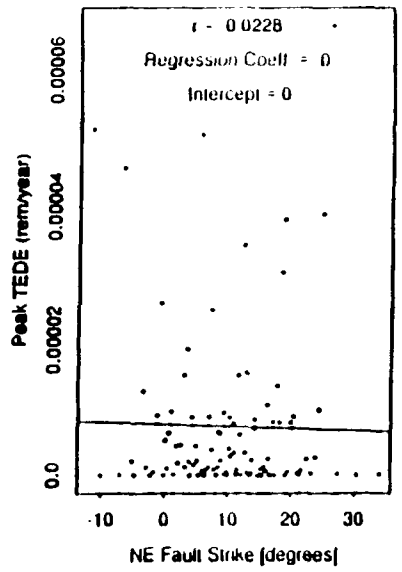




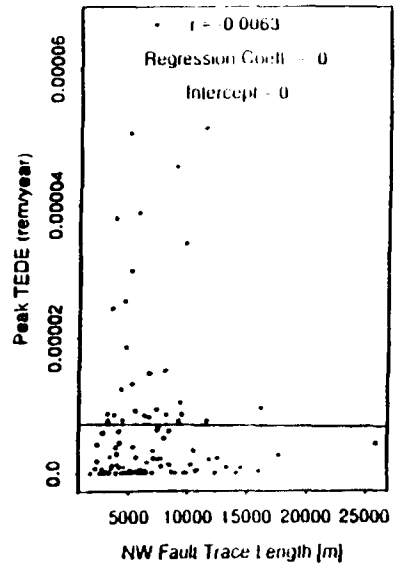
Parameter No. 5



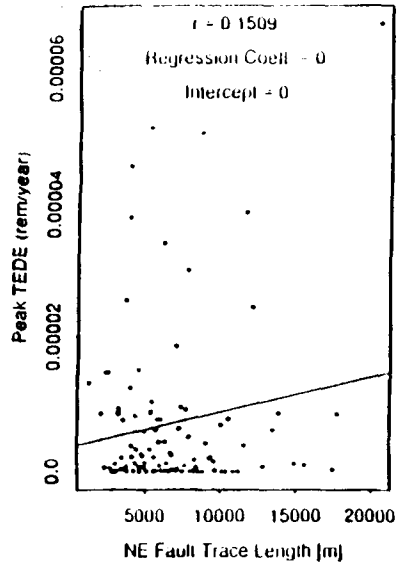
Parameter No. 6



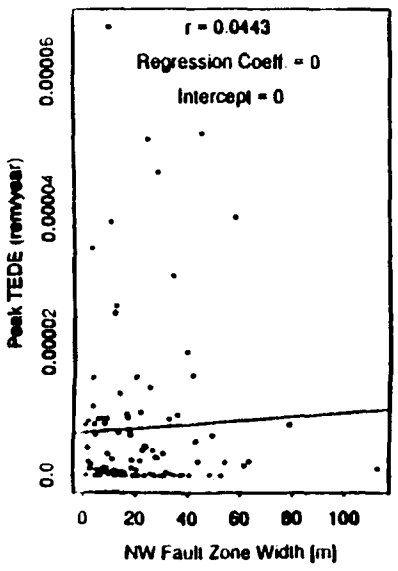
Parameter No. 7



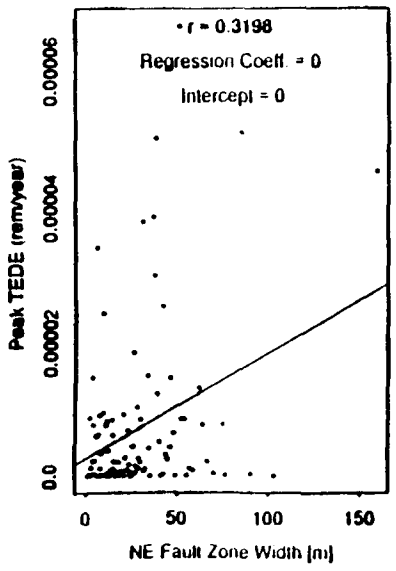
Parameter No. 8



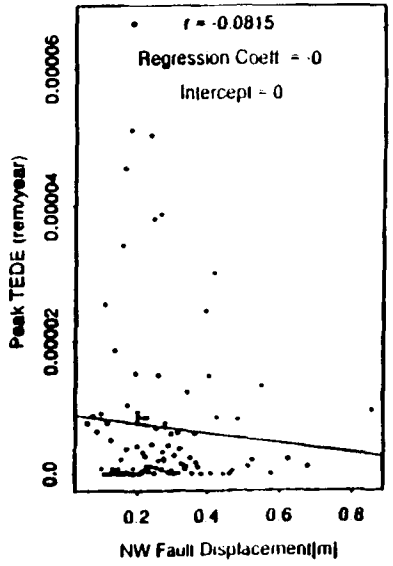
Parameter No. 9



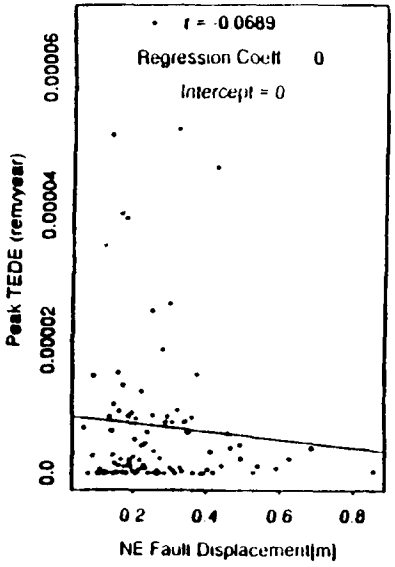
Parameter No. 10



Parameter No. 11

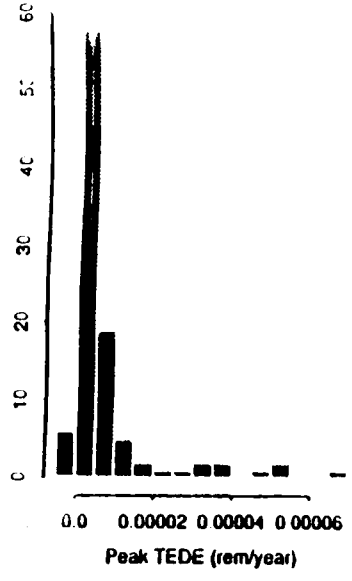


Parameter No. 12

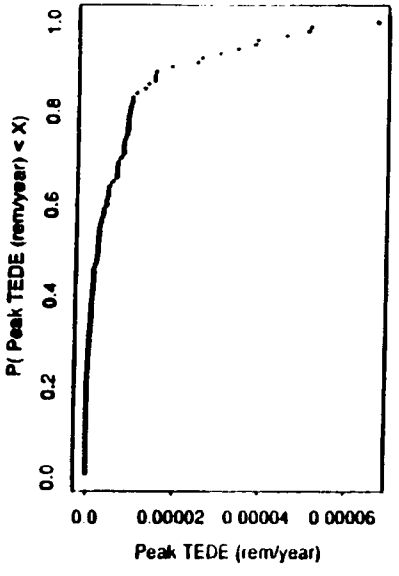


20 km Scenario
Summary Plots for Peak TEDE (rem/year)

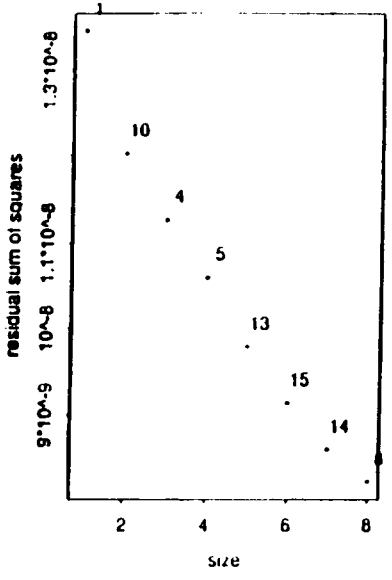
Frequency Distribution



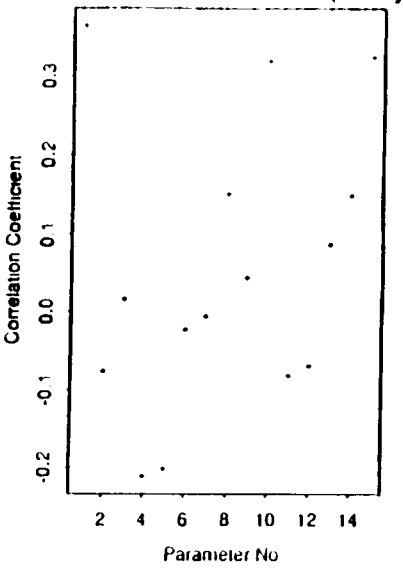
Cumulative Frequency



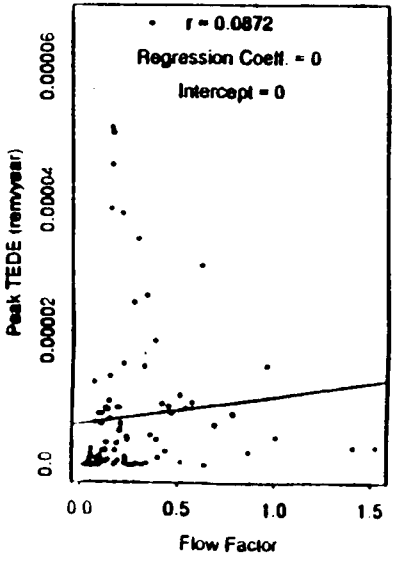
Stepwise Reduction in Error



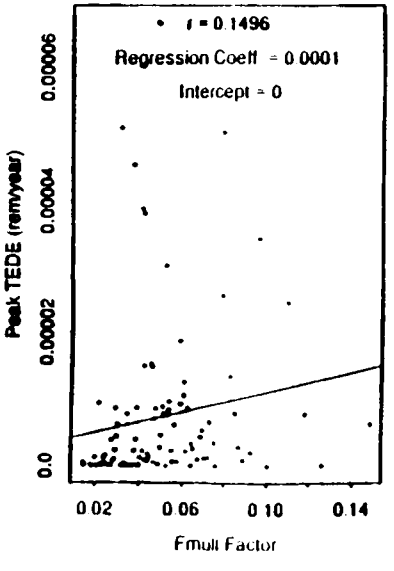
Correlation Coefficients
Parameter ~ Peak TEDE (rem/year)



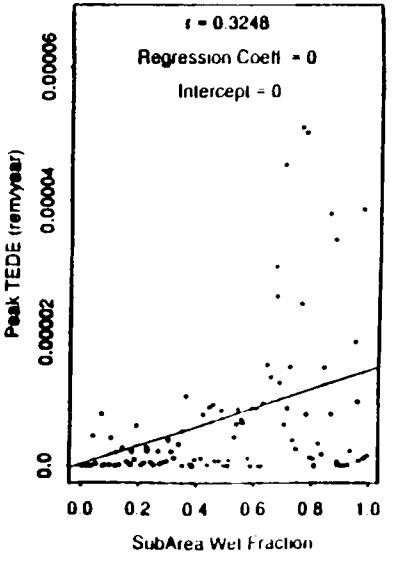
Parameter No. 13



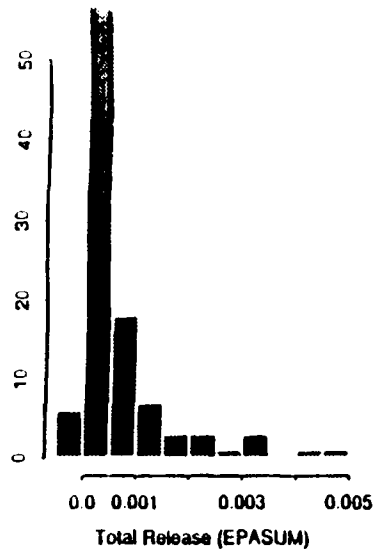
Parameter No. 14

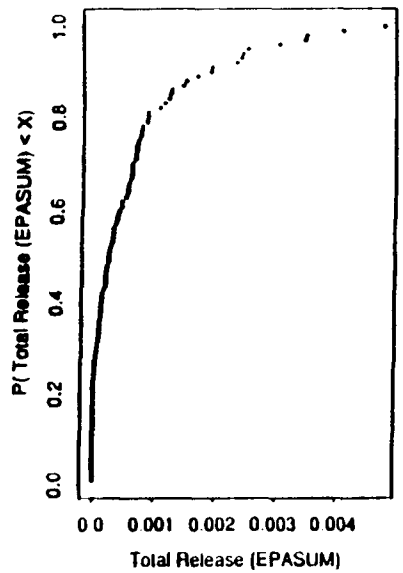


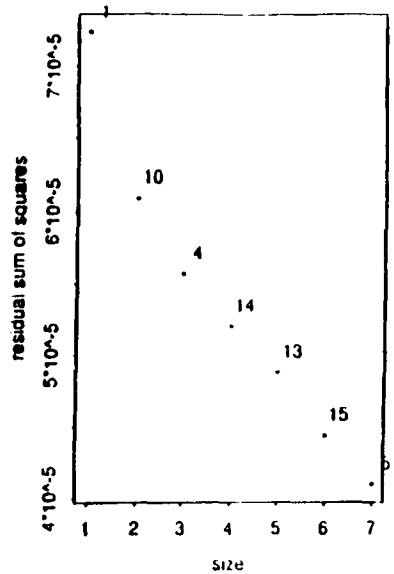
Parameter No. 15

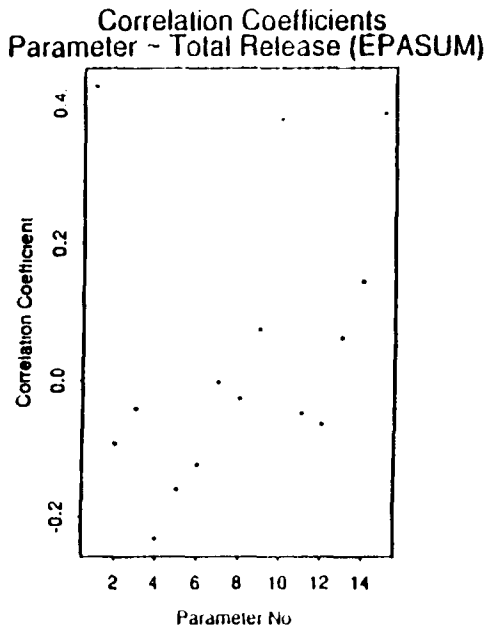


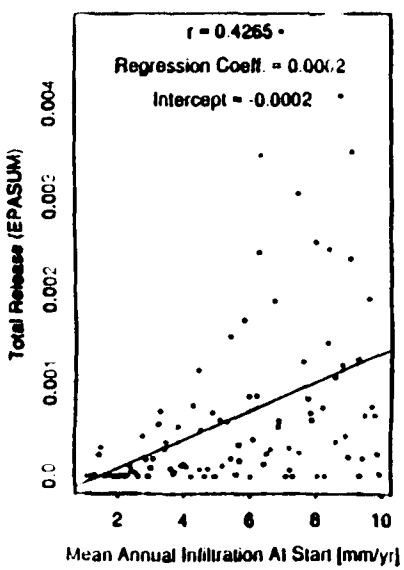
20 km Scenario
Summary Plots for Total Release (EPASUM)

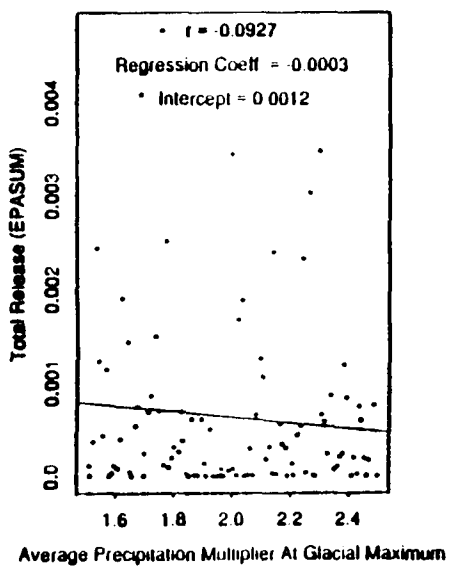


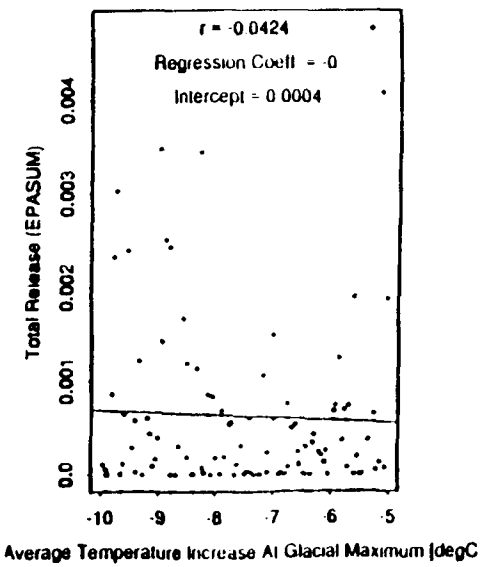


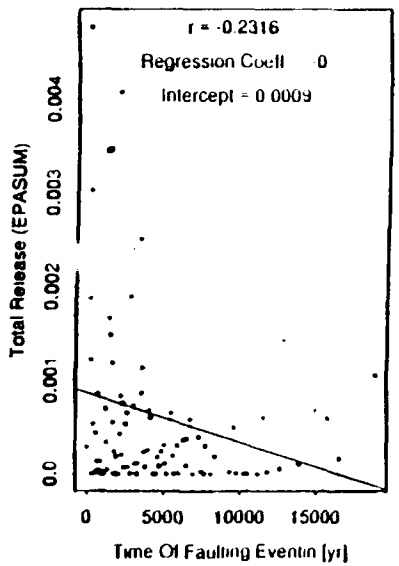




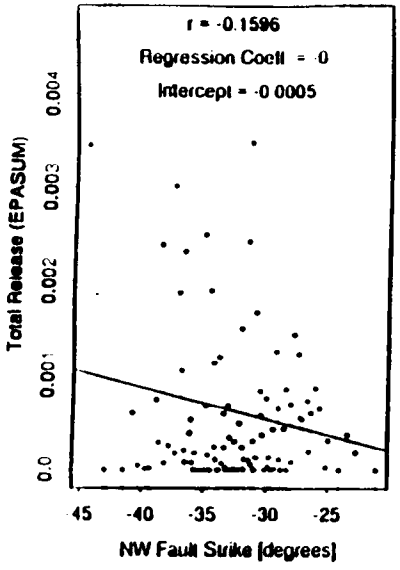




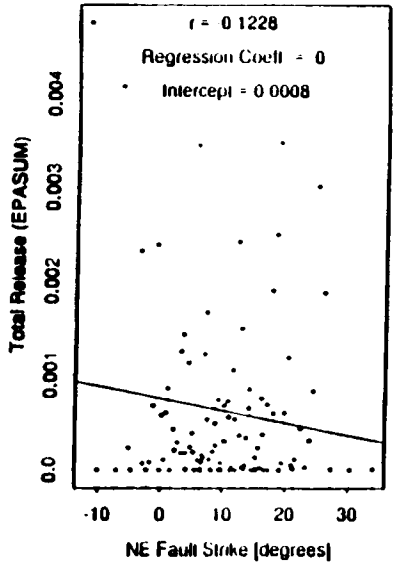




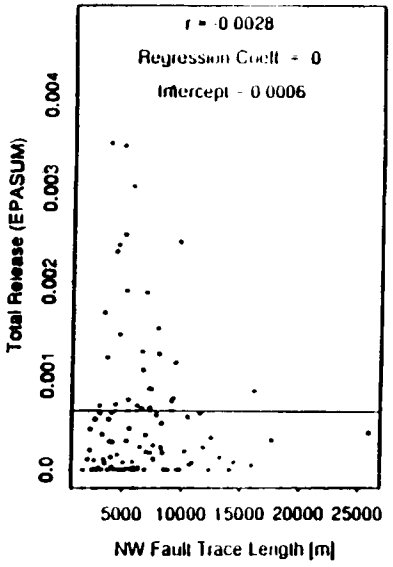
Parameter No. 5



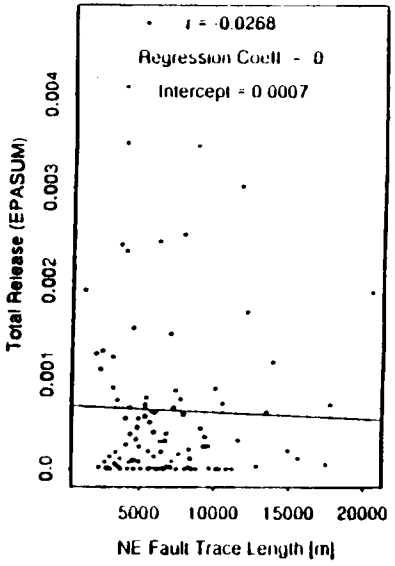
Parameter No. 6



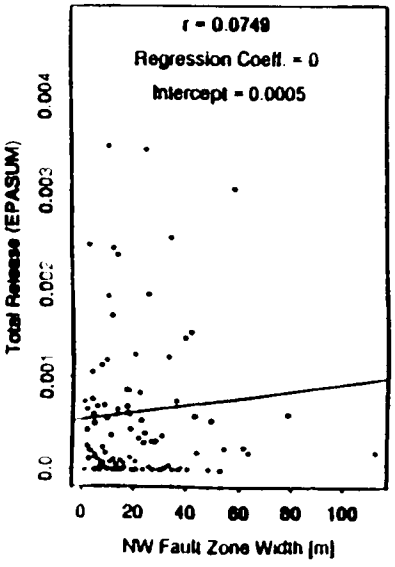
Parameter No. 7



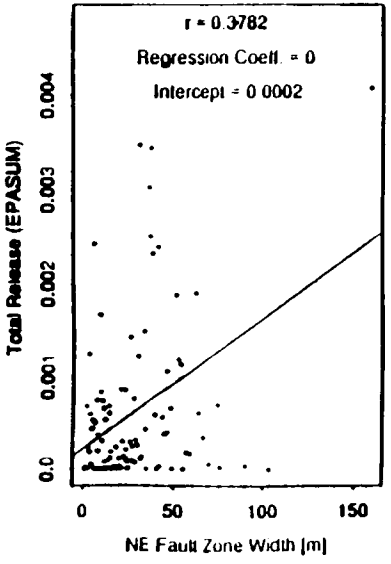
Parameter No. 8



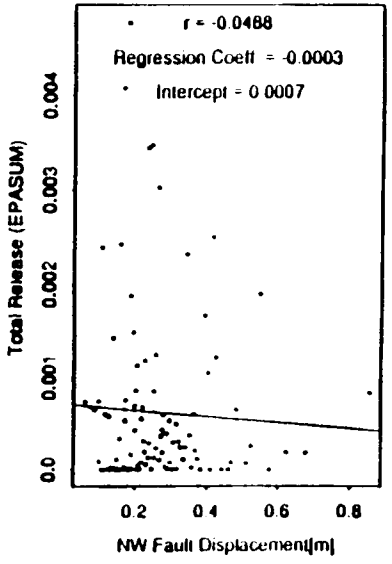
Parameter No. 9



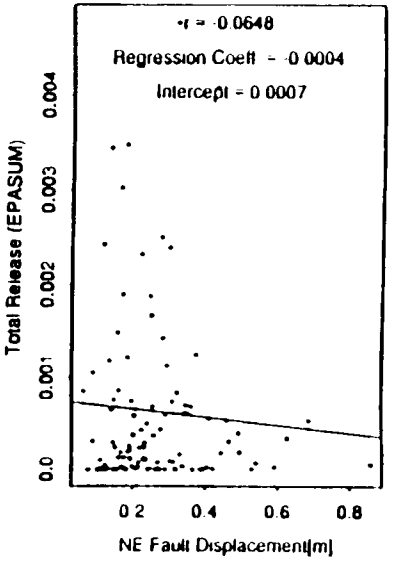
Parameter No. 10



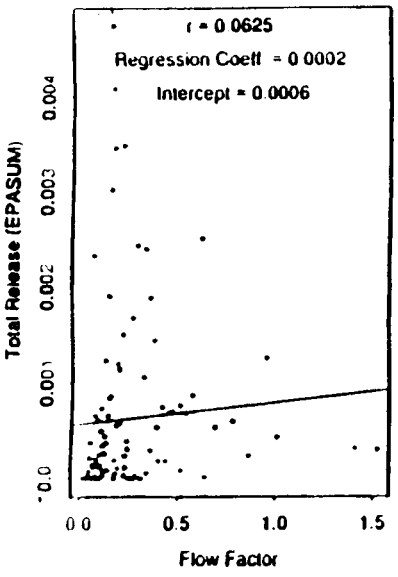
Parameter No. 11



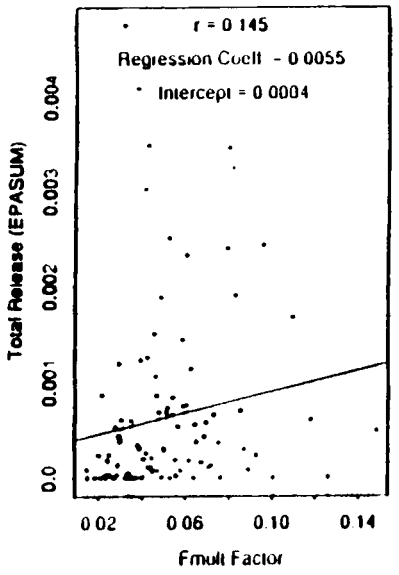
Parameter No. 12



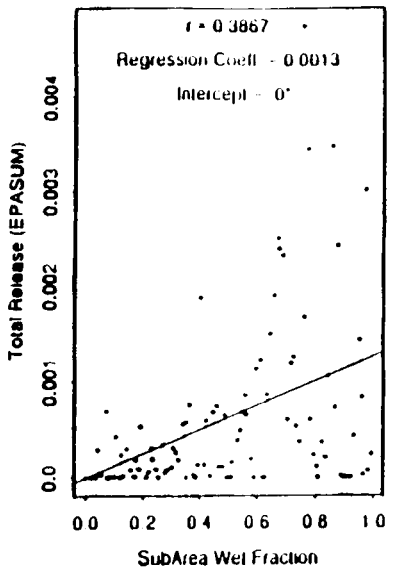
Parameter No. 13



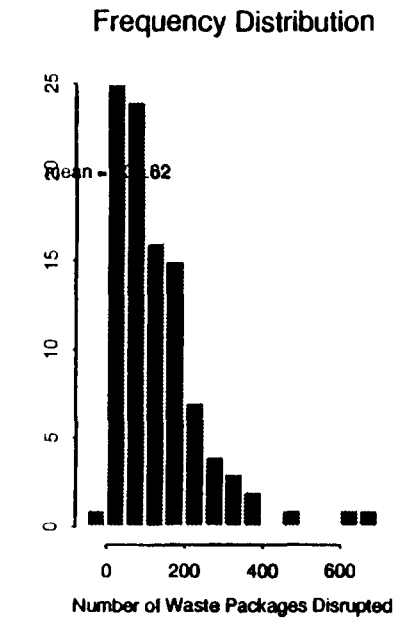
Parameter No. 14

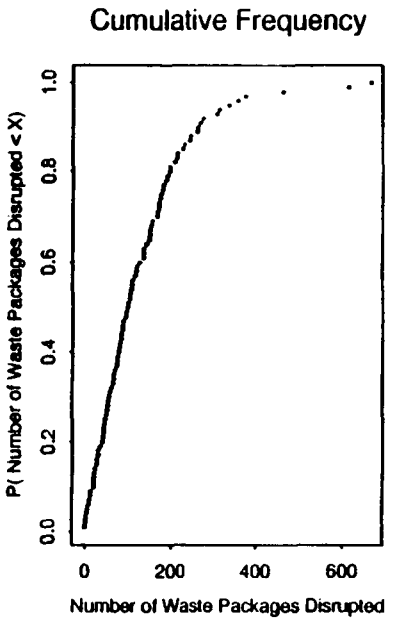


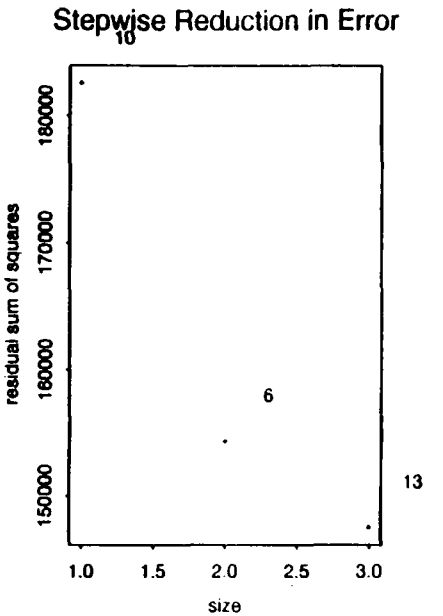
Parameter No. 15

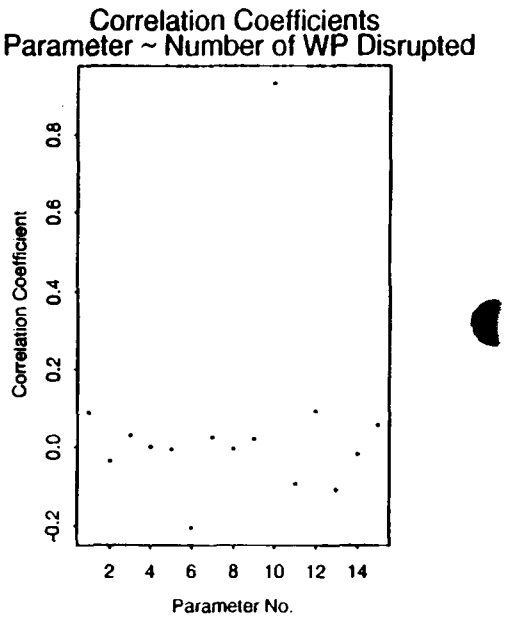


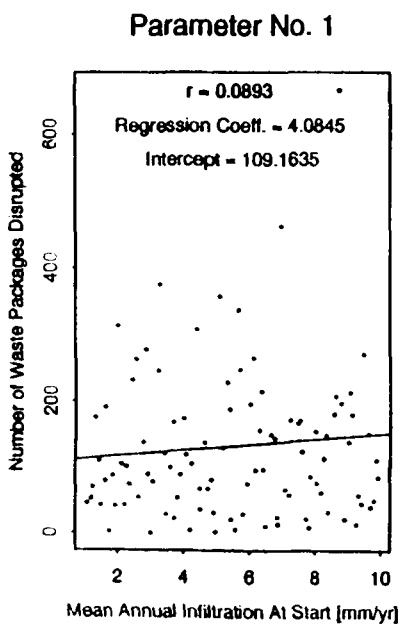
20 km Scenario
Summary Plots for Number of Waste Packages Disrupted

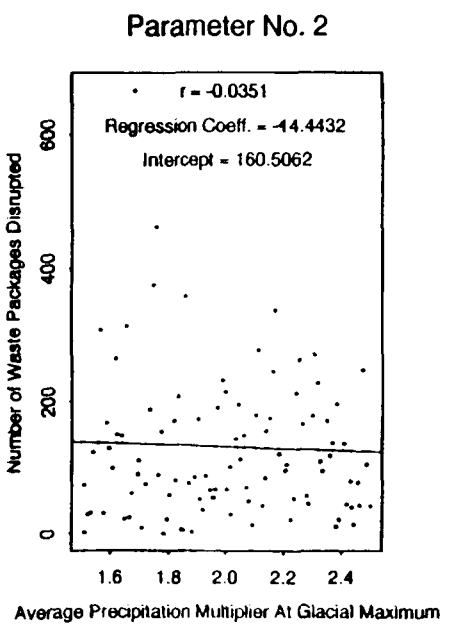


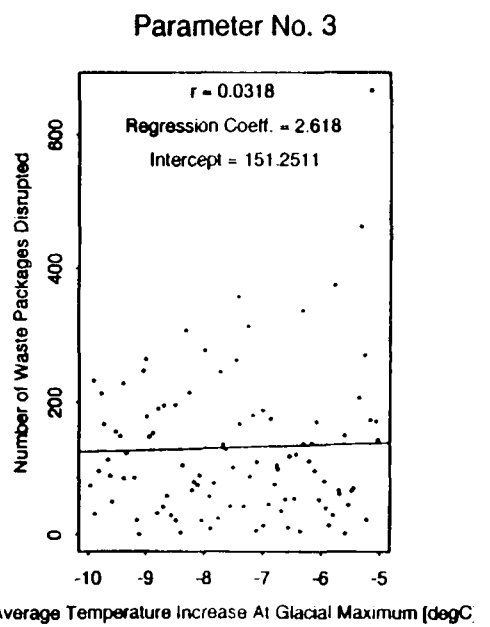


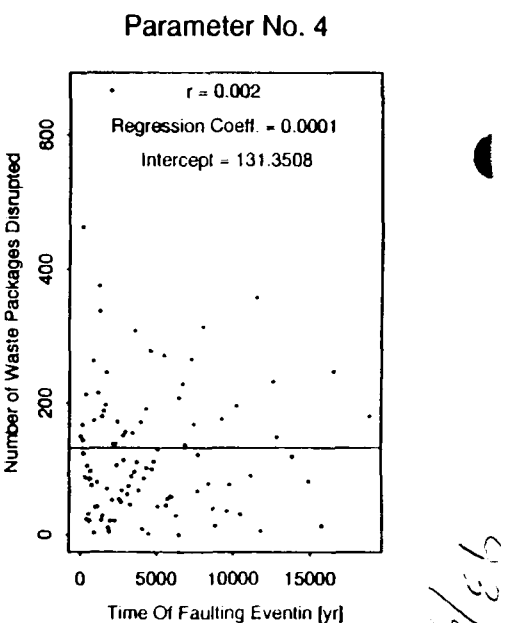




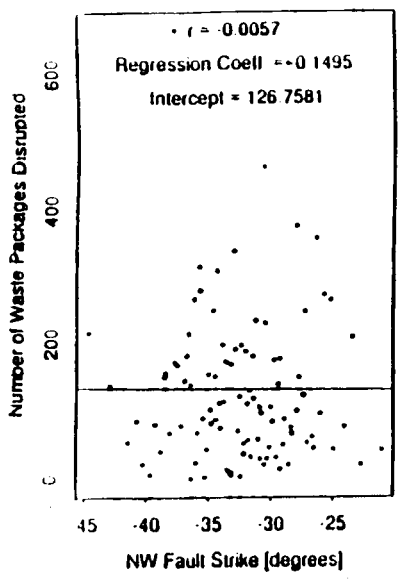




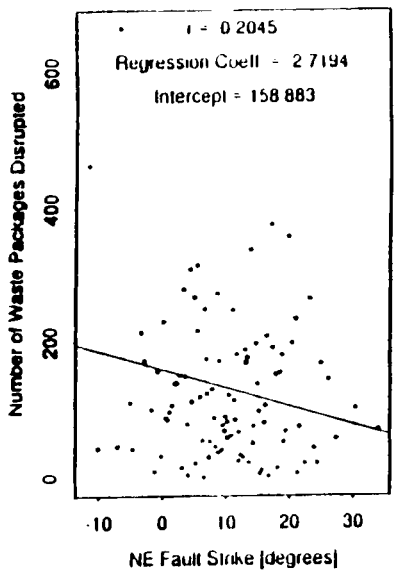




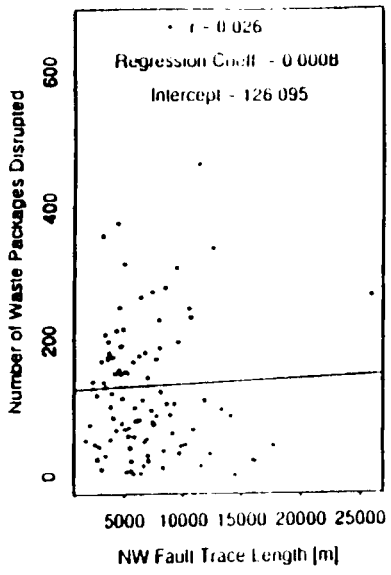
Parameter No. 5



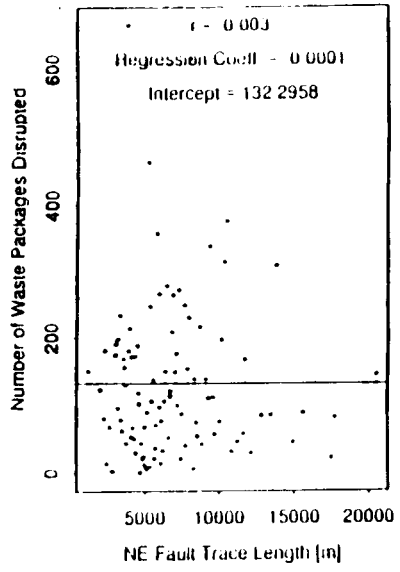
Parameter No. 6



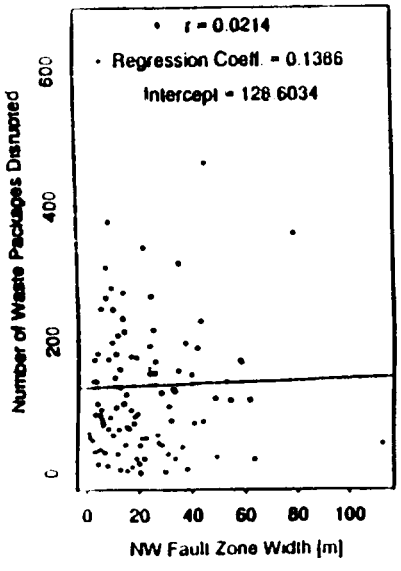
Parameter No. 7



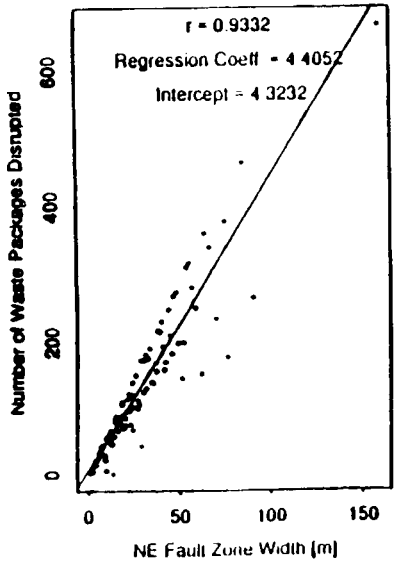
Parameter No. 8



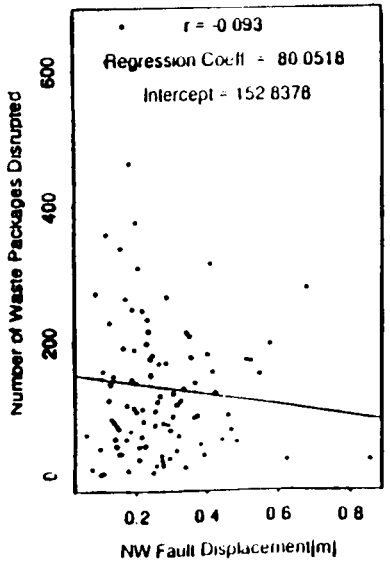
Parameter No. 9



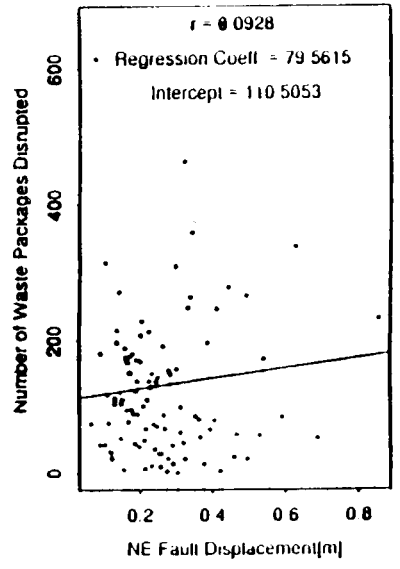
Parameter No. 10



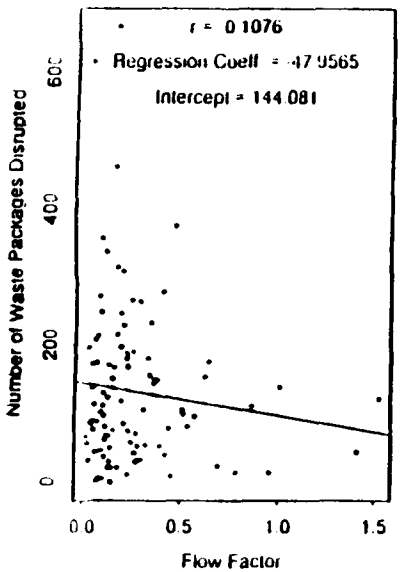
Parameter No. 11



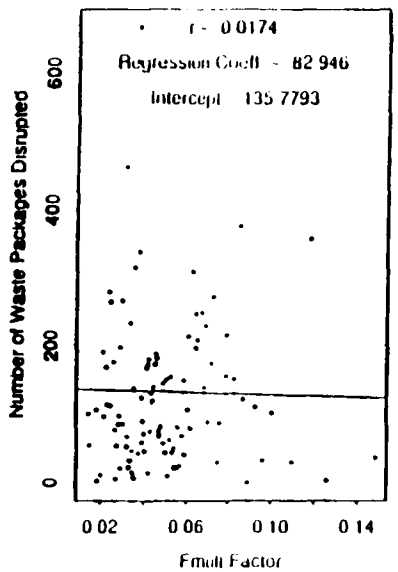
Parameter No. 12



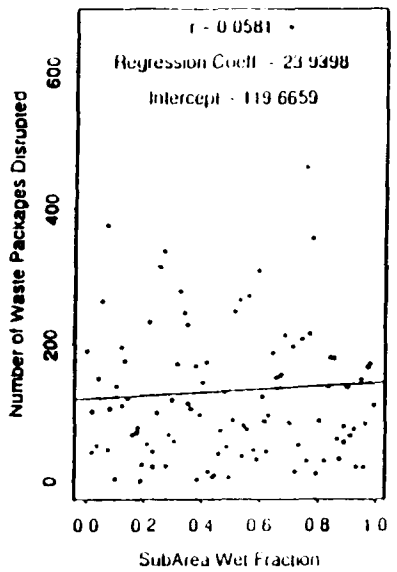
Parameter No. 13



Parameter No. 14



Parameter No. 15



54/54