March 9, 1994
San Francisco, CA

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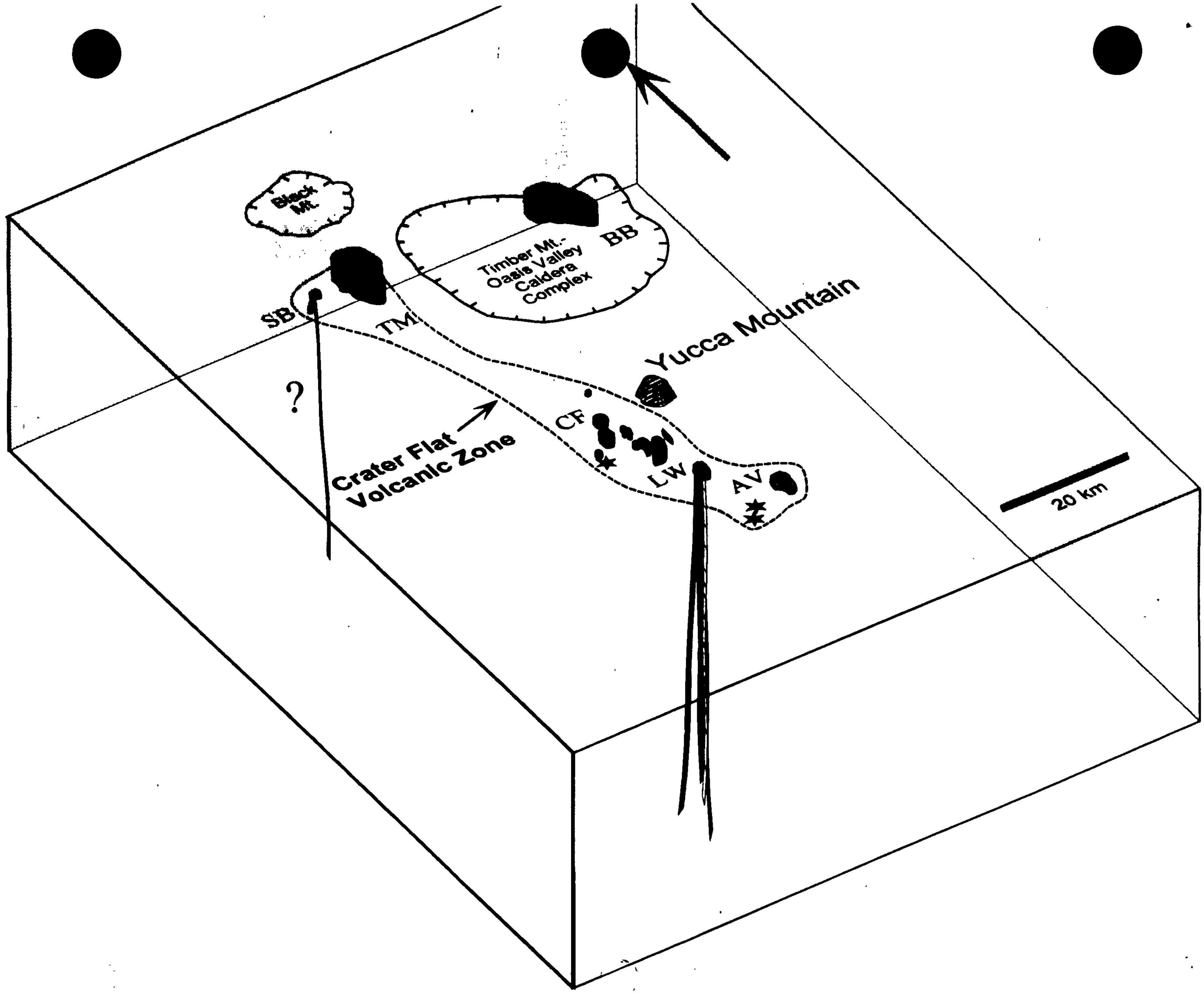
Los Alamos National Laboratory

Probabilistic Volcanic Risk Assessment


Black Mt.
Timber Mt.-
Oasis Valley
Caldera
Complex
BB
SB
TM
Yucca Mountain
?
CF
Crater Flat
Volcanic Zone
LW
AV
20 km

Conditional Probability Model
Magmatic Disruption

$$Pr_{dr} = Pr(E3 \text{ given } E2, E1) Pr(E2 \text{ given } E1) Pr(E1)$$

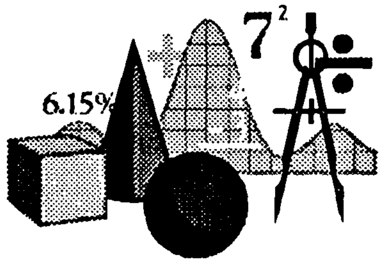
where

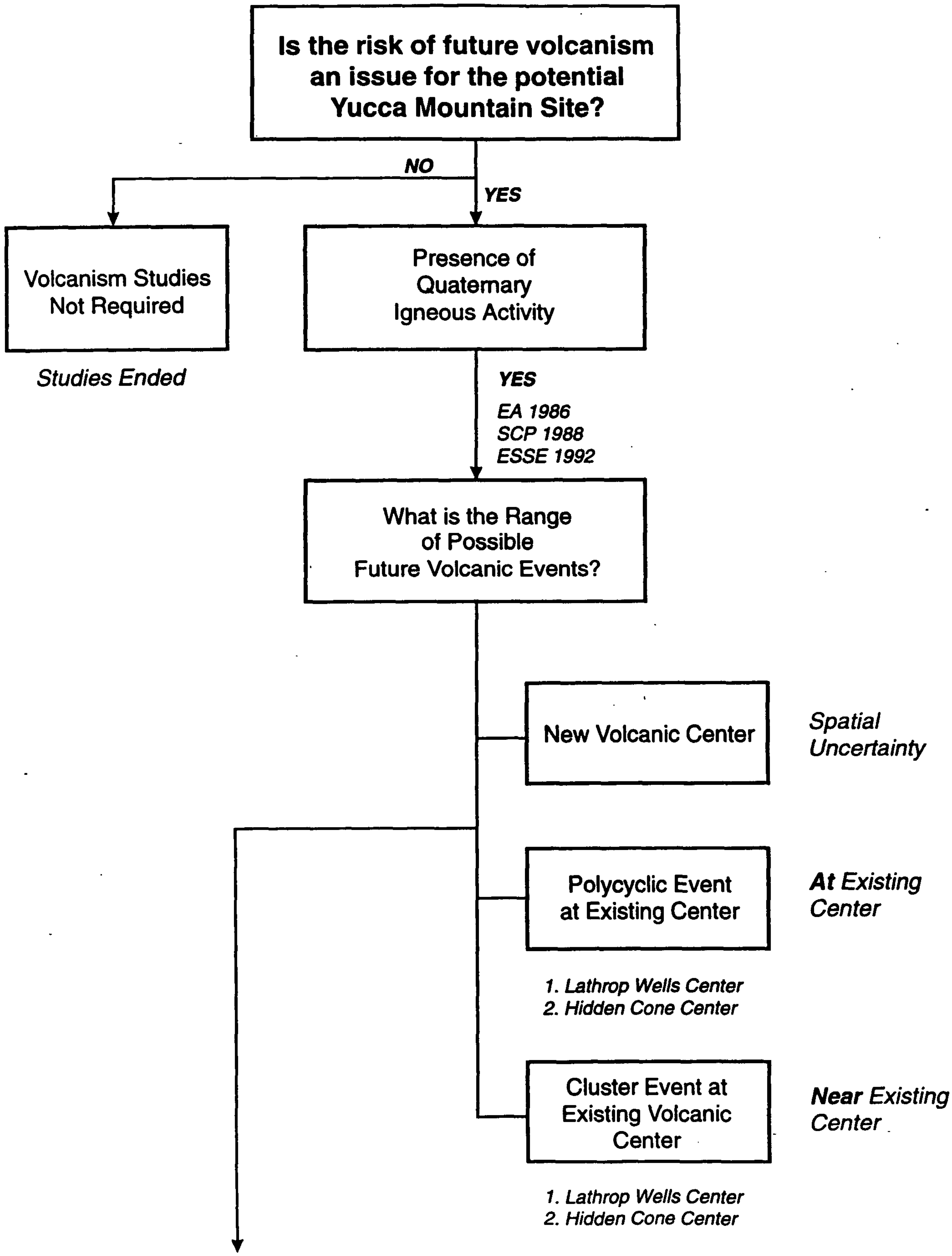
E1: recurrence rate of volcanic events
E2: probability a future event intersects a specified area
E3: release of radionuclides to the accessible environment

E1: volcanic centers, volcanic clusters, intrusions, polycyclic episodes, cluster episodes

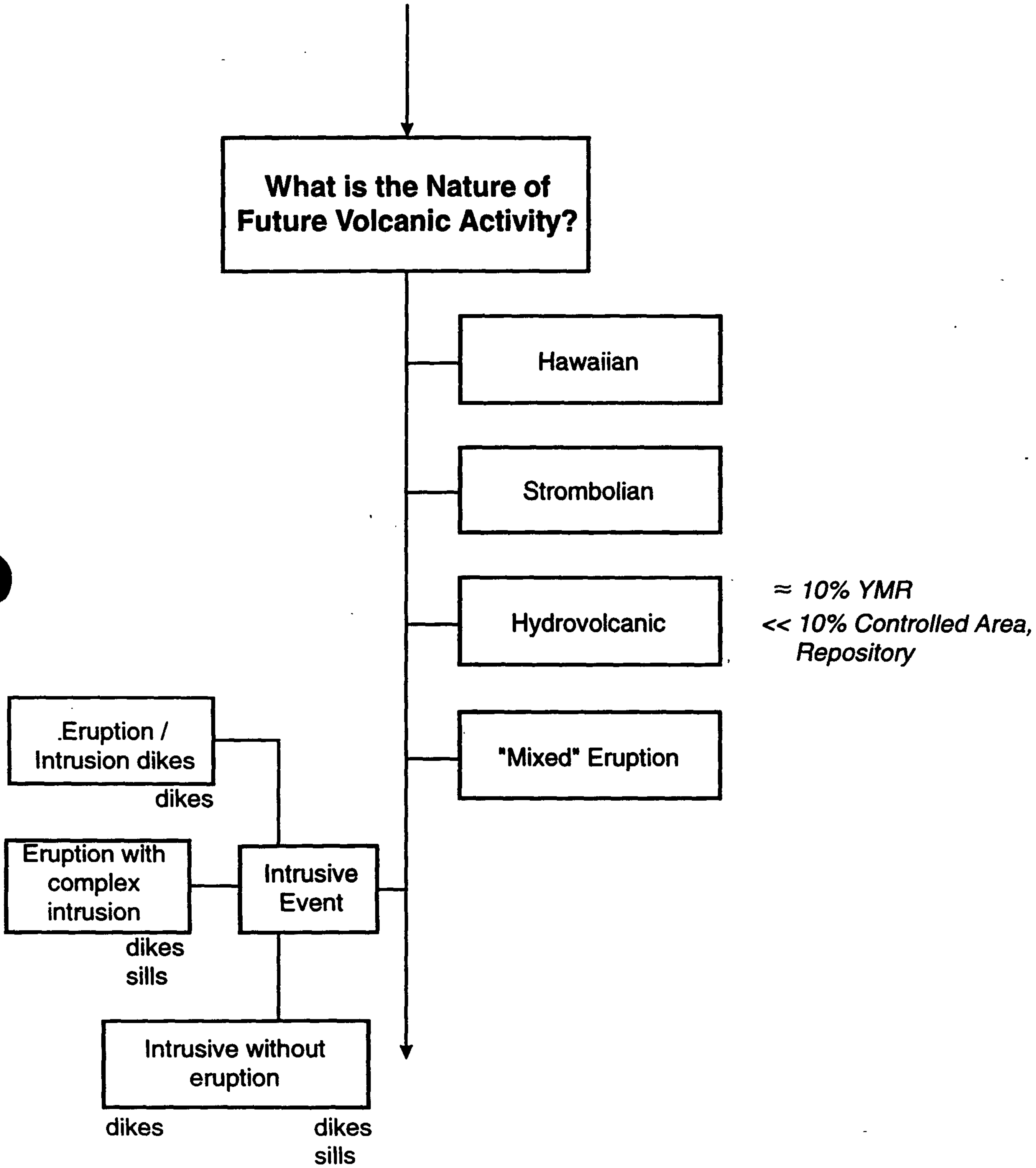
E2: repository, controlled area, waste isolation system (Yucca Mountain region)

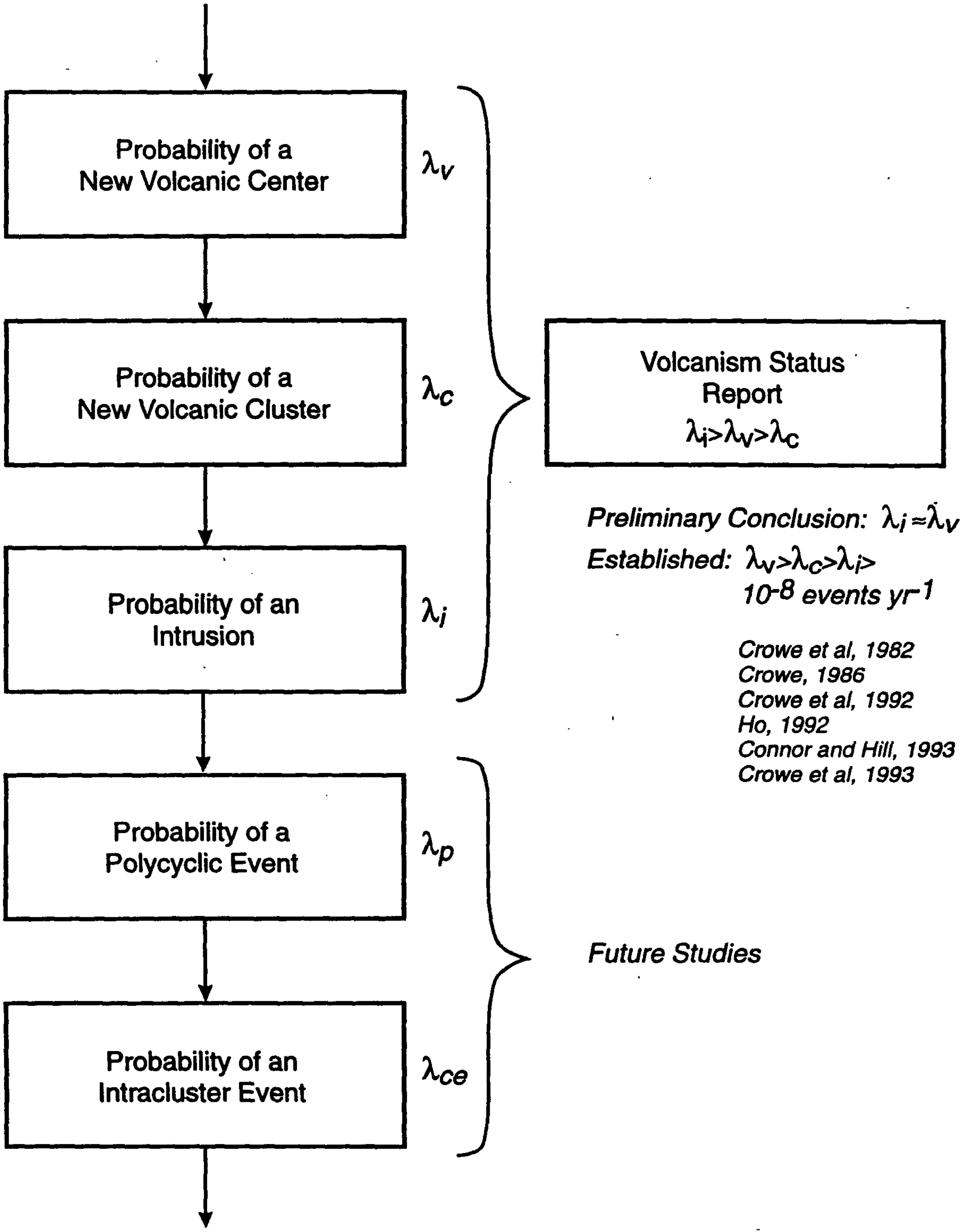
E3: direct releases (eruptions), coupled releases

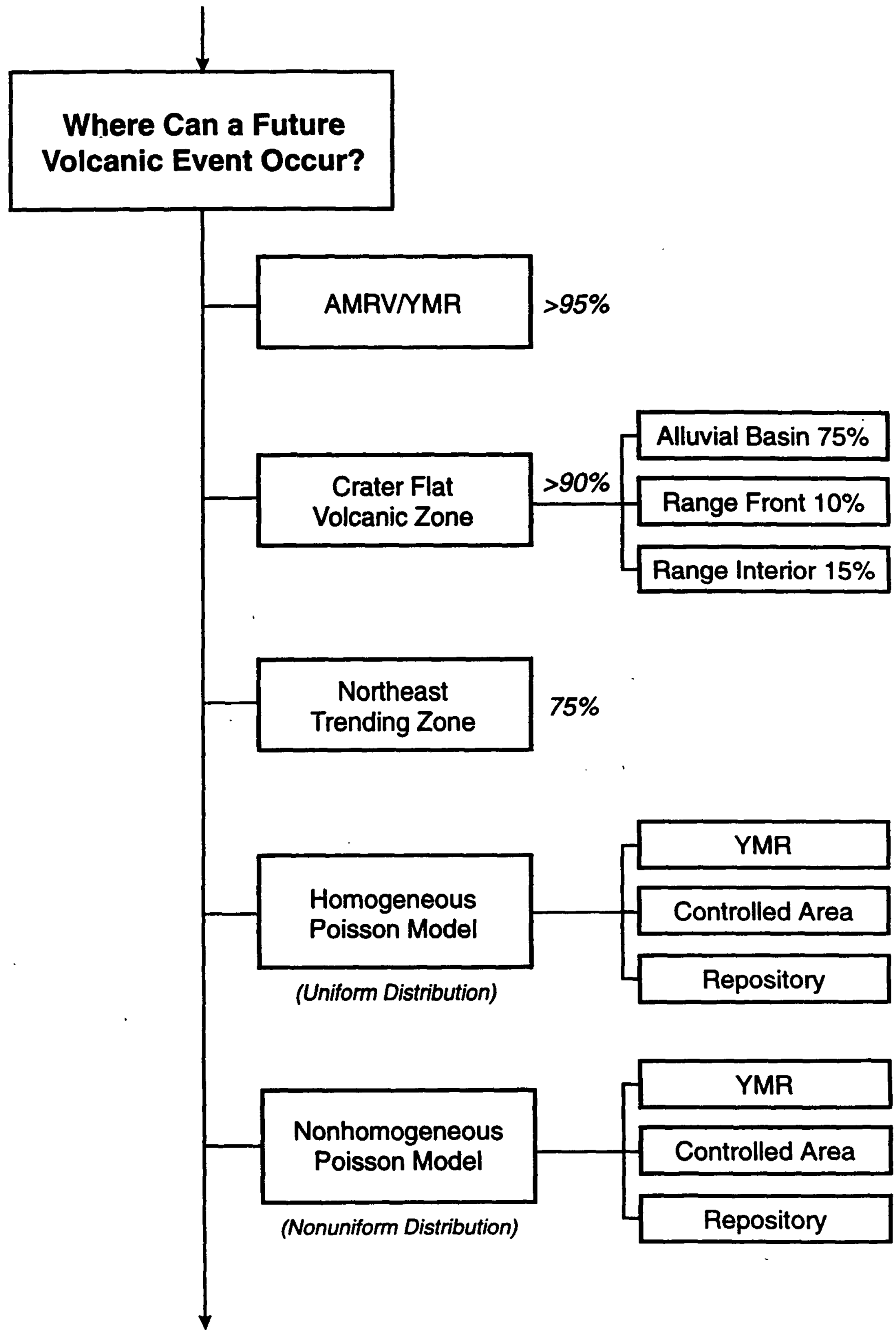


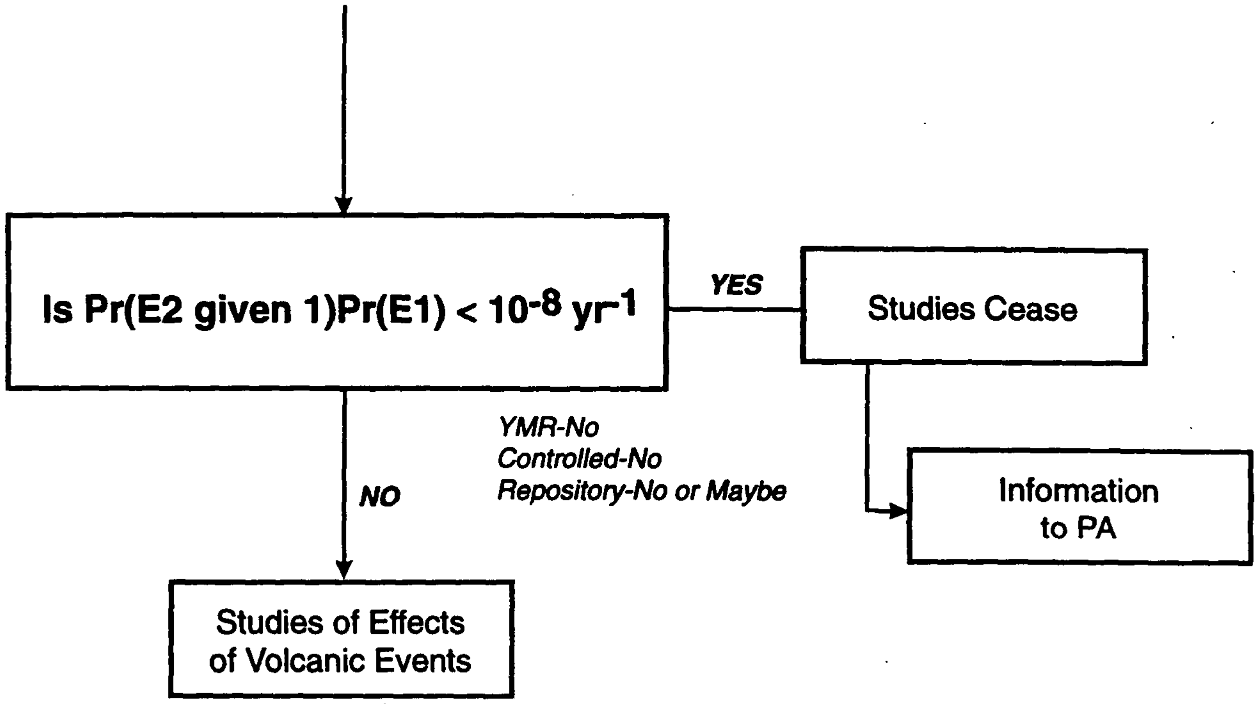


YMVOLCAN1.DOE.CD4/1-31-94


What is the Nature of Future Volcanic Activity?
Hawaiian
Strombolian
Hydrovolcanic
≈ 10% YMR
<< 10% Controlled Area, Repository
"Mixed" Eruption
.Eruption / Intrusion dikes
dikes
Eruption with complex intrusion
dikes
sills
Intrusive Event
Intrusive without eruption
dikes
dikes
sills


Probability of a New Volcanic Center
λv
Probability of a New Volcanic Cluster
λc
Probability of an Intrusion
λi
Probability of a Polycyclic Event
λp
Probability of an Intracluster Event
λce
Volcanism Status Report
λi>λv>λc
Preliminary Conclusion: λi ≈ λv
Established: λv>λc>λi> 10-8 events yr-1
Crowe et al, 1982
Crowe, 1986
Crowe et al, 1992
Ho, 1992
Connor and Hill, 1993
Crowe et al, 1993
Future Studies


Where Can a Future Volcanic Event Occur?
AMRV/YMR
>95%
Crater Flat Volcanic Zone
>90%
Alluvial Basin 75%
Range Front 10%
Range Interior 15%
Northeast Trending Zone
75%
Homogeneous Poisson Model
(Uniform Distribution)
YMR
Controlled Area
Repository
Nonhomogeneous Poisson Model
(Nonuniform Distribution)
YMR
Controlled Area
Repository


Is Pr(E2 given 1)Pr(E1) < 10-8 yr-1
YES
Studies Cease
Information to PA
NO
YMR-No
Controlled-No
Repository-No or Maybe
Studies of Effects of Volcanic Events

Volcanism Studies
Data Paradox

1. Limited number of Volcanic Centers in the Yucca Mountain Region

    7 Quaternary volcanic centers
    3 Time-space clusters

    12 Pliocene volcanic centers
    4-5 Time-space clusters

2. **Fundamental Assumption**

Volcanic record is too limited for robust calculations **statistical significance** **goodness of fit**

3. Risk assessment

    Volcanic record of the Yucca Mountain region
        forward projection for probability estimates
        mid-point estimates
    Analog volcanic fields
        bounds on rates of volcanic events
    Multiple Alternative Models
        recurrence models
        structural and spatial models
        distribution models

4. Multiple Models are Possible
    cannot be proven or disproven with record

***effect* on probability distribution**

Volcanic Event
Probability Model

1. Range of definitions
   one of the reasons for differences in probability estimates

   Cluster model: spatial and time related clusters of centers
   Center model: new volcanic center
   Event model: individual vents or fissures in a center

2. Polycyclic Volcanism
   episodes of volcanic activity at an ***existing*** volcanic center
   new concept: confusion in probability applications

   Polycyclic events have been included in center or cluster models

3. Polycyclic Volcanism
   emphasis of future probabilistic studies

4. Consistent Application of Defined Models

Volcanism Studies
RISK SIMULATION

1. Simulation Modeling is used to test significance, sensitivity

   ensure: all alternative models are included/evaluated
   occurrence probability
   risk

NOT UNDERESTIMATED

BUT . . . .

ALTERNATIVE MODELS MUST BE PLAUSIBLE PHYSICALLY

2. New Perspective: Probability Estimates
   Previous Estimations:
   probability bounds
   Review Organizations
   worse or worst case emphasis

3. Revised Estimates

   Regulatory bounds
   Analog bounds
   Mid-point estimates: geologic record

unbiased probability distributions

4. DOE will assess distributions

   Regulatory perspective

Recurrence Models
Probability Estimates

1. Time-Series Data

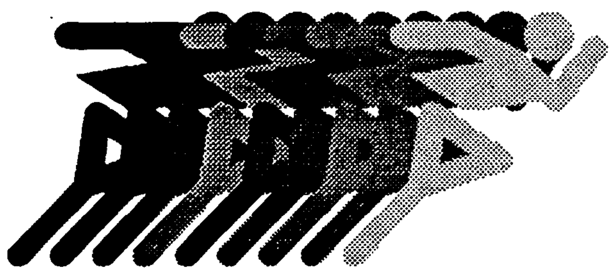
   Data too limited to be significant
   repose intervals

2. Homogeneous and Nonhomogeneous Poisson Models

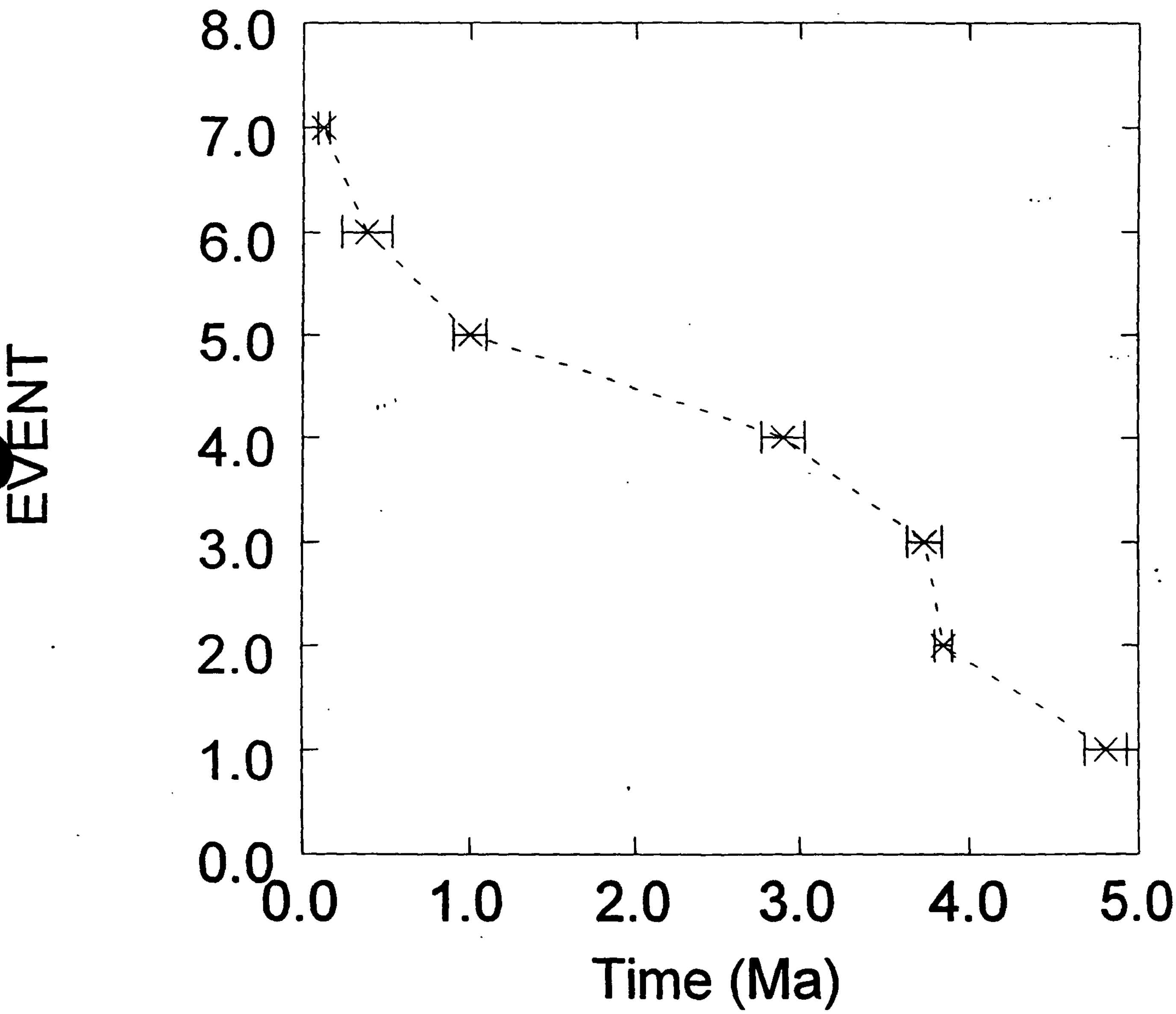
   Centers, Clusters

3. Time-Volume Models

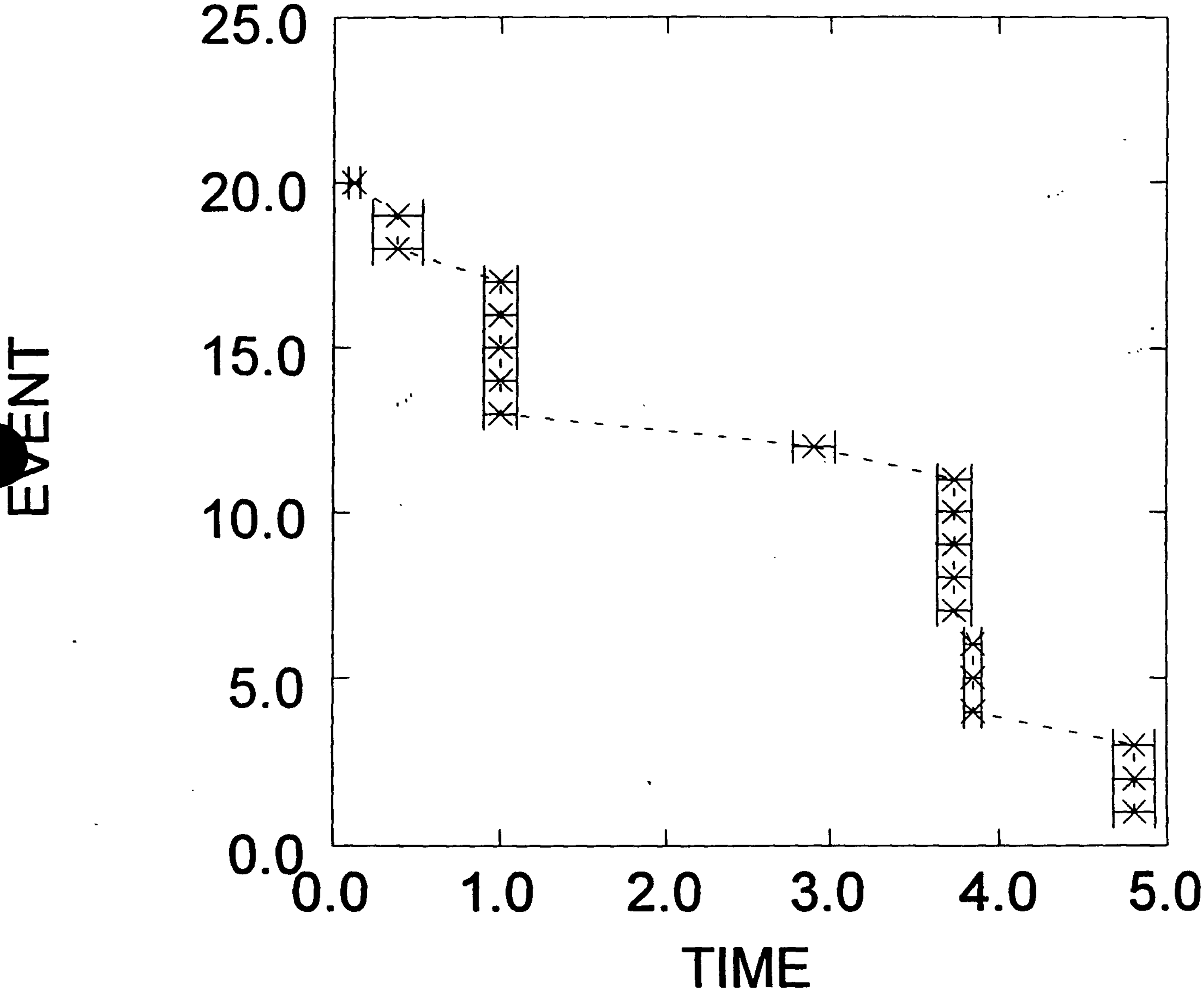
   Magma Output Rate
   mostly non-significant regression calculations

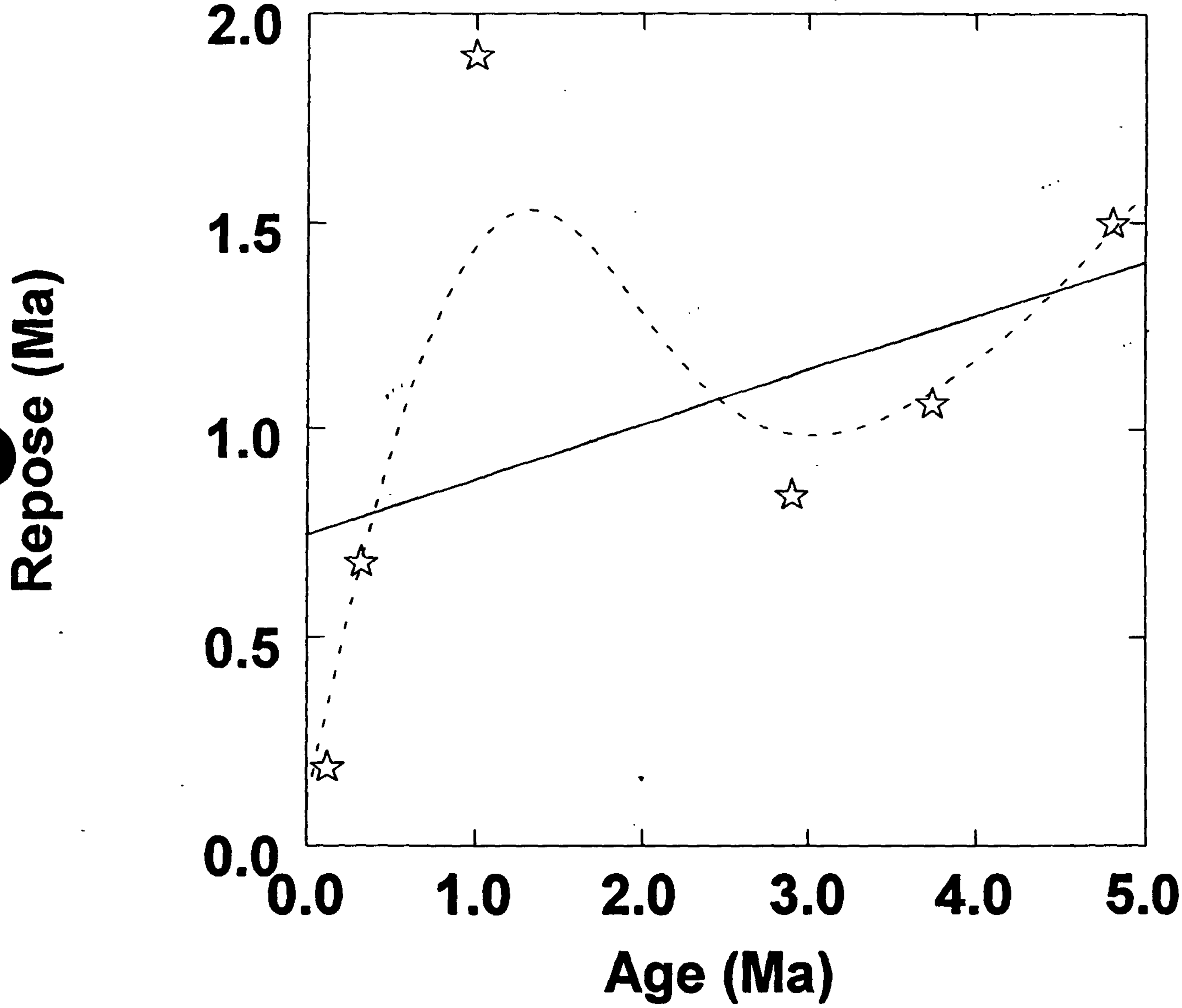


(Las Vegas, Nevada: Home of the World's Most Predictable Volcano)



8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
EVENT
0.0
1.0
2.0
3.0
4.0
5.0
Time (Ma)


25.0
20.0
15.0
10.0
5.0
0.0
EVENT
0.0
1.0
2.0
3.0
4.0
5.0
TIME



2.0
1.5
1.0
0.5
0.0
Repose (Ma)
0.0
1.0
2.0
3.0
4.0
5.0
Age (Ma)

Table 7.5. Table of Homogeneous Poisson Models for Volcanic Events (E1) in the YMR.

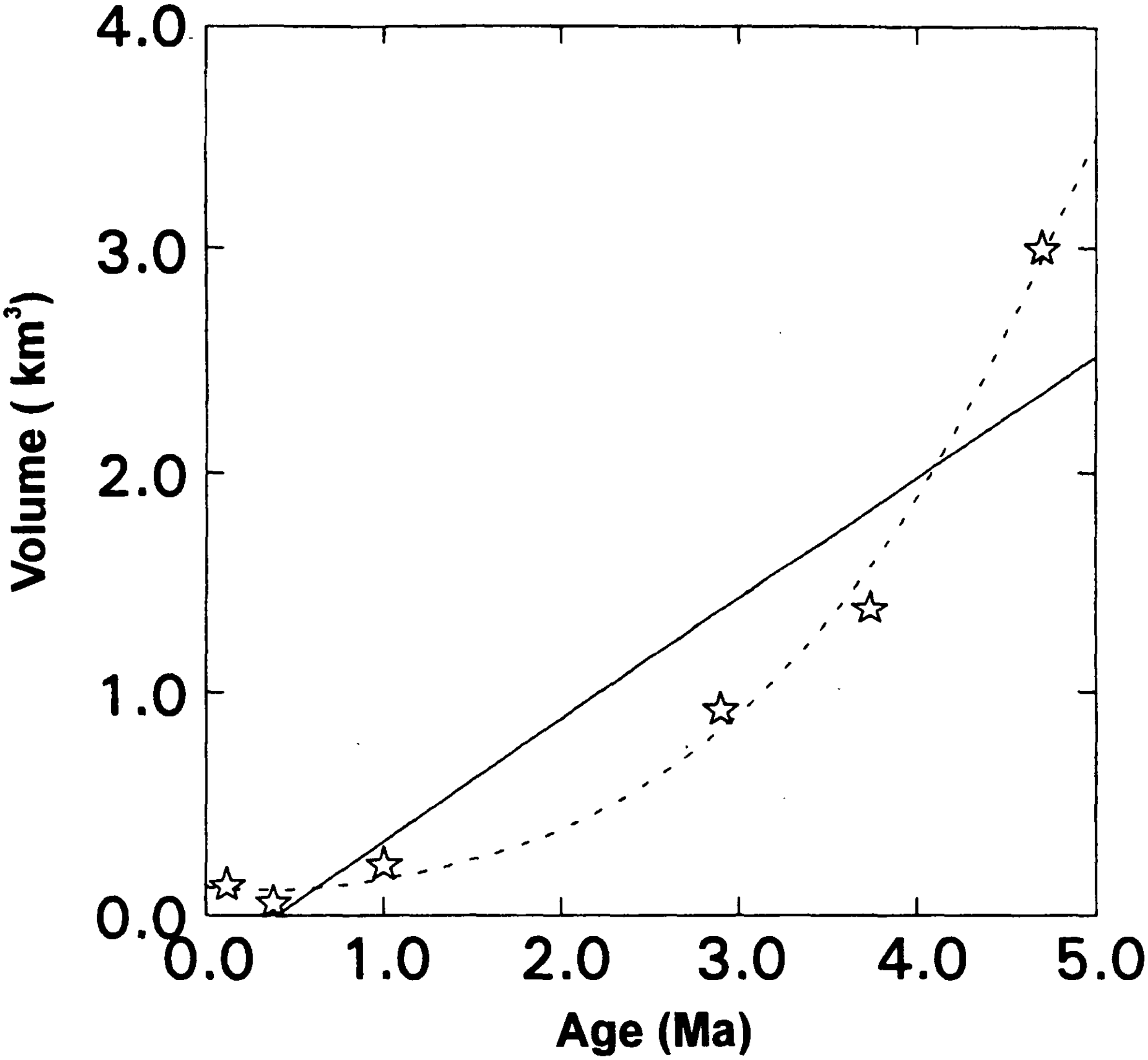
Interval	Model	Interval (yrs)	Minimum events yr^{-1}	Maximum events yr^{-1}	Most Likely events yr^{-1}
Quaternary		2.00E+06			
	Poisson Events		3	8	6
	Poisson Rates		1.5E-06	4.0E-06	3.0E-06
	Stress-Dike		3	8	5
	Stress-Dike Rates		1.5E-06	4.0E-06	2.5E-06
Volcanic Cycle*		4.80E+06			
	Poisson Events		8	19	12
	Poisson Rates		1.7E-06	4.0E-06	2.5E-06
	Stress-Dike		8	10	10
	Stress-Dike Rates		1.7E-06	2.1E-06	2.1E-06
Quaternary		1.60E+06			
	Poisson Events		3	8	6
	Poisson Rates		1.9E-06	5.0E-06	3.7E-06
	Stress-Dike		3	6	5
	Stress-Dike Rates		1.9E-06	3.7E-06	3.1E-06
Quaternary Accelerated*		1.00E+06			
	Poisson Events		3	8	7
	Poisson Rates		3.0E-06	8.0E-06	6.0E-06
	Stress-Dike		3	6	5
	Stress-Dike Rate		3.0E-06	6.0E-06	5.0E-06
Summary Statistics (all Models)		***Mean***	***2.0E-06***	***4.6E-06***	***3.5E-06***
		Median	***1.8E-06***	***4.0E-06***	***3.1E-06***
		Geomean	***1.9E-06***	***4.3E-06***	***3.3E-06***
		Std Deviation	***0.6E-06***	***1.7E-06***	***1.3E-06***
Summary Statistics (Preferred Models)*		***Mean***	***2.3E-06***	***5.0E-06***	***3.9E-06***
		Median	***2.3E-06***	***5.0E-06***	***3.8E-06***
		Geomean	***2.3E-06***	***4.5E-06***	***3.6E-06***
		Std Deviation	***0.75E-06***	***2.53E-06***	***1.8E-06***

* Preferred models are models where the event counts span an interval that corresponds to cycles of volcanic activity (4.8 Ma to present; and 1.0 Ma to present.

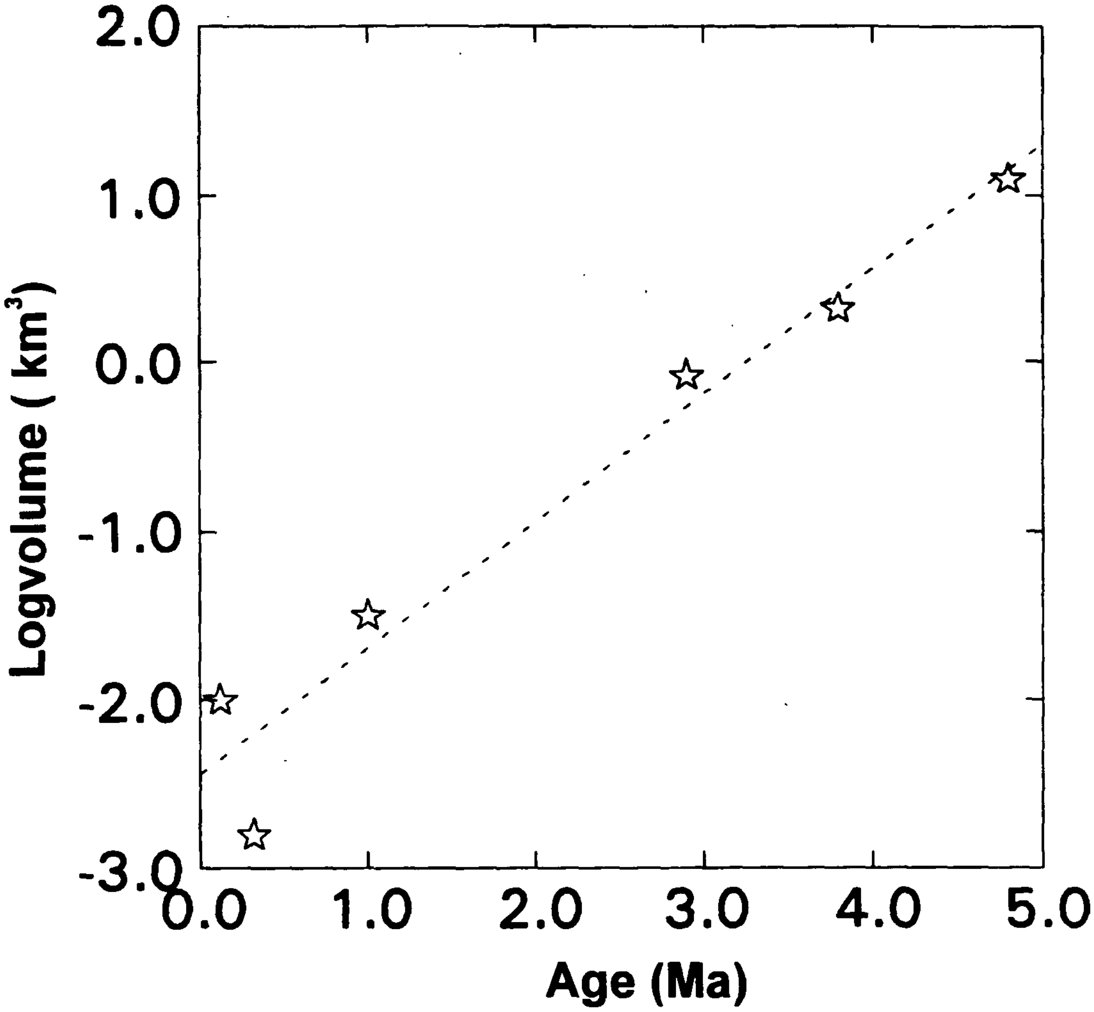
Table 7.6 Nonhomogeneous Recurrence Models (E1) for the YMR

Interval	Model	Interval (yrs)	Minimum events yr^{-1}	Maximum events yr^{-1}	Most Likely events yr^{-1}
Quaternary		2.00E+06			
	Events		3	8	6
	Beta		3.10	2.10	2.30
	Weibull Rate		4.6E-06	8.4E-06	6.9E-06
	Stress Dike		3	8	5
	Beta		3.1	2.10	2.10
	Weibull Rate		4.6E-06	8.4E-06	5.2E-06
Volcanic Cycle*		4.80E+06			
	Events		8	19	12
	Beta		0.84	0.72	1.00
	Weibull Rate		1.4E-06	2.9E-06	2.5E-06
	Stress Dike		8	10	10
	Beta		0.84	0.9	0.9
	Weibull Rate		1.4E-06	1.9E-06	1.9E-06
Quaternary Rate		1.60E+06			
	Events		3	8	6
	Beta		1.7	1.4	1.7
	Weibull Rate		3.2E-06	7.0E-06	6.4E-06
	Stress Dike		3	6	5
	Beta		1.7	1.7	1.8
	Weibull Rate		3.2E-06	6.4E-06	5.6E-06
Quaternary Accelerated*		1.00E+06			
	Events		3	8	6
	Beta		0.94	0.60	0.70
	Weibull Rate		2.8E-06	4.8E-06	4.2E-06
	Stress Dike		3	6	5
	Beta		0.94	0.70	0.60
	Weibull Rate		2.8E-06	4.2E-06	3.0E-06
Summary Statistics (all models)		***Mean***	***3.0E-06***	***5.5E-06***	***4.6E-06***
		Median	***3.0E-06***	***5.6E-06***	***4.7E-06***
		Geomean	***2.8E-06***	***4.9E-06***	***4.0E-06***
		Std Deviation	***1.2E-06***	***2.4E-06***	***1.9E-06***
Summary Statistics (Preferred Modesls)*		***Mean***	***2.1E-06***	***3.4E-06***	***2.9E-06***
		Median	***2.1E-06***	***3.5E-06***	***2.7E-06***
		Geomean	***2.0E-06***	***3.2E-06***	***2.8E-06***
		Std Deviation	***8.08E-07***	***1.30E-06***	***9.76E-07***

* Preferred models are models with event counts spanning intervals that correspond to cycles of volcanic activity (4.8 Ma to present; 1.0 Ma to present)



4.0
3.0
2.0
1.0
0.0
Volume (km³)
0.0
1.0
2.0
3.0
4.0
5.0
Age (Ma)



2.0
1.0
0.0
-1.0
-2.0
-3.0
Logvolume (km³)
0.0
1.0
2.0
3.0
4.0
5.0
Age (Ma)

Table 7.9 Age, Cumulation Volume, Magma Ouput Rates, Generation Rates, and Event Rates for Pliocene and Quaternary Volcanic Centers of the YMR.

EVENT MODELS	AGE (Ma)	VOLUME	CUMVOL	MOR* ($m^3 yr^{-1}$)			
Event: Case I							
Thirsty Mesa	4.8	3.0E+09	3.0E+09	305	GR** (mean)	GR (geomean)	GR (median)
Amargosa Valley	3.8	3.0E+08	3.3E+09	268	2.5E+06	1.2E+06	9.7E+05
CF3.7	3.7	6.8E+08	4.0E+09		2.8E+06	1.4E+06	1.1E+06
Buckboard	2.9	9.2E+08	4.9E+09		ER*** (mean)	ER (geomean)	GR (median)
CF1.0	1.0	2.3E+08	5.1E+09		4.0E-07	8.2E-07	1.0E-06
Sleeping Butte	.32	5.9E+07	5.2E+09		3.5E-07	7.2E-07	9.0E-07
Lathrop Wells	.12	1.4E+08	5.3E+09				
Mean	*7.6E+08*	*Median*	*3.0E+08*				
Geomean	*3.8E+08*	*Std Deviation*	*1.0E+09*				
Event: Case II					**GR (mean)**	**GR (geomean)**	**GR (median)**
CF1.0	**1.0**	**2.3E+08**	**2.3E+08**	**305**	**4.6E+05**	**4.0E+05**	**4.5E+05**
Sleeping Butte	**.32**	**5.9E+07**	**2.9E+08**	**268**	**5.2E+05**	**4.5E+05**	**5.1E+05**
Lathrop Wells	**.12**	**1.4E+08**	**4.3E+08**		**ER (mean)**	**ER (geomean)**	**ER (median)**
Mean	*1.4E+08*	*Median*	*1.4E+08*		**2.2E-06**	**2.5E-06**	**2.2E-06**
Geomean	*1.2E+08*	*Std Deviation*	*8.5E+07*		**1.9E-06**	**2.2E-06**	**1.9E-06**
Event: Case III					**GR (mean)**	**GR (geomean)**	**GR (median)**
CF-North	**1.0**	**1.7E+08**	**1.7E+08**	**305**	**2.7E+05**	**2.1E+05**	**1.9E+05**
CF-South	**1.0**	**6.0E+07**	**2.3E+08**	**268**	**3.1E+05**	**2.3E+05**	**2.1E+05**
Hidden	**.32**	**3.5E+07**	**2.6E+08**		**ER (mean)**	**ER (geomean)**	**ER (median)**
Black Peak	**.32**	**2.4E+07**	**2.9E+08**		**3.7E-06**	**4.9E-06**	**5.3E-06**
Lathrop	**.12**	**1.4E+08**	**4.3E+08**		**3.2E-06**	**4.2E-06**	**4.6E-06**
Mean	*8.6E+07*	*Median*	*6.0E+07*				
Geomean	*6.5E+07*	*Std Deviation*	*6.5E+07*				
*MOR : Magma Output Rate					*Preferred Models*	*Generation Rate*	*Event Rate*
**GR= Generation Rate					*Preferred mean*	*2.9E+05*	*3.4E-06*
***ER = Event Rate					*Preferred median*	*2.0E+05*	*5.0E-06*
					Preferred geomean	*2.2E+05*	*4.5E-06*

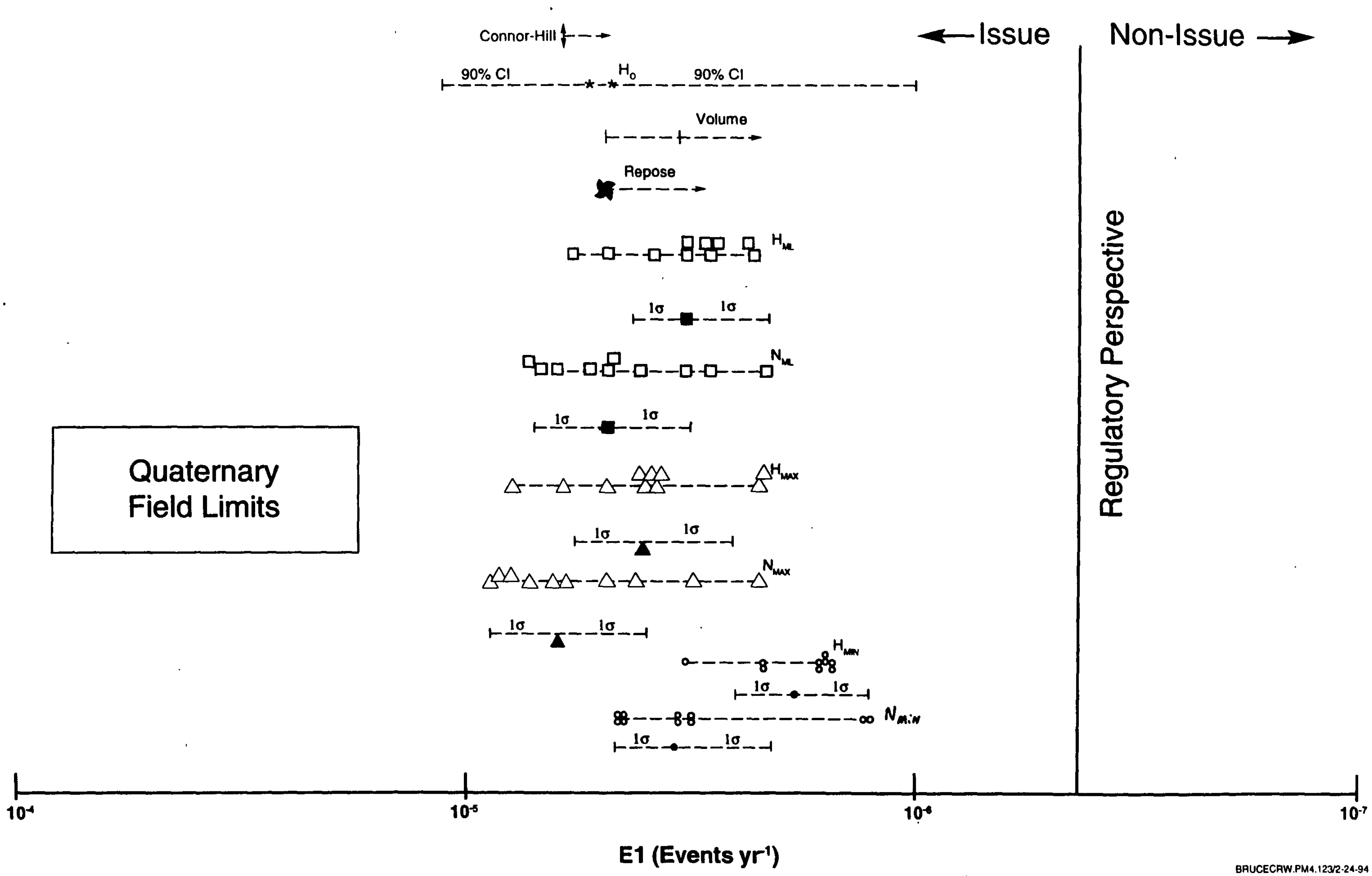


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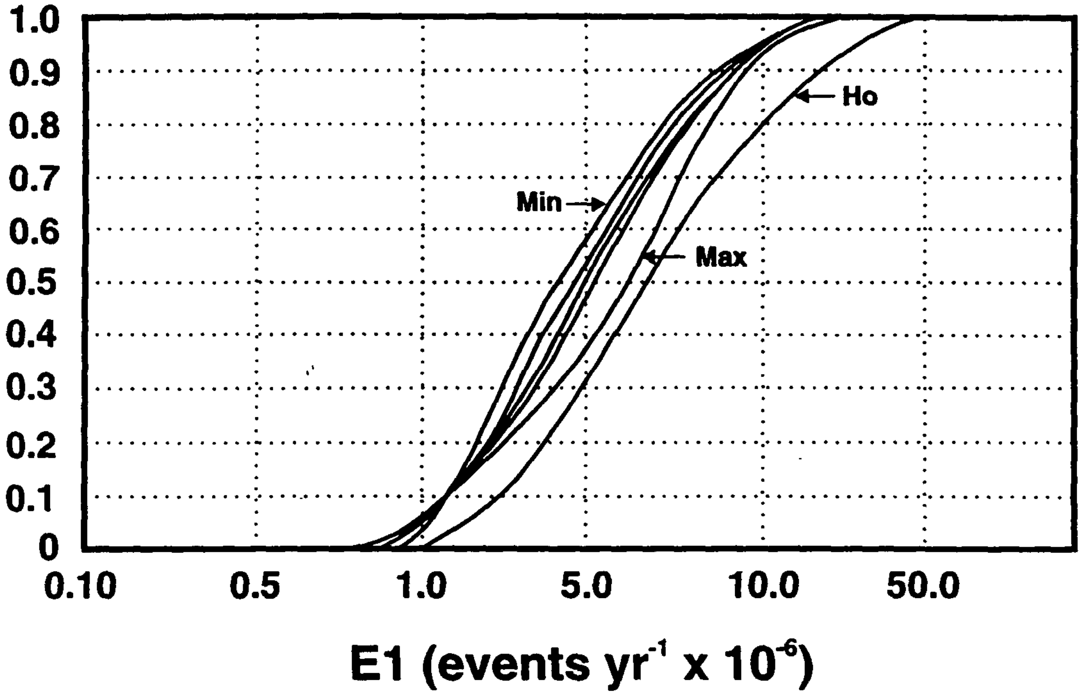
Table 7.10 Simulation Matrix , expected values and matrix statistics for E1, the recurrence rate.

Model	**Min**	**Most Likely**	**Max**	**Min(all)**	**Max(all)**				
Homogeneous: All	2.1E-06	3.6E+00	4.6E-06	1.5E-06	8.0E-06				
Homogeneous: Pref	2.3E-06	4.1E-06	5.0E-06	1.7E-06	8.0E-06				
Nonhomogeneous: All	3.0E-06	4.4E-06	5.5E-06	1.4E-06	8.4E-06				
Nonhomogeneous: Pref	2.1E-06	2.9E-06	3.4E-06	1.4E-06	4.8E-06				
Repose			5.3E-06						
Volume-Predict	1.0E-06	3.2E-06	5.3E-06						
Distribution Boundaries	**quartiles**	**10%/1% limits**	**10%/5% limits**	**10%/10% limits**	**Normal (1 σ)**				
Risk Simulations	**Sim1**	**Sim2**	**Sim3**	**Sim4**	**Sim5**	*Mean*	*Median*	*Geomean*	*Std Dev*
Homogeneous: All	4.8E-06	4.4E-06	4.9E-06	5.4E-06	3.6E-06	*4.6E-06*	*4.8E-06*	*4.6E-06*	*6.8E-07*
Homogeneous: Pref	4.8E-06	4.1E-06	5.0E-06	5.5E-06	4.1E-06	*4.8E-06*	*4.8E-06*	*4.8E-06*	*5.2E-07*
Nonhomogeneous: All	4.8E-06	4.6E-06	5.1E-06	5.6E-06	4.5E-06	*4.9E-06*	*4.8E-06*	*4.9E-06*	*4.4E-07*
Nonhomogeneous: Pref	4.8E-06	4.3E-06	4.8E-06	5.4E-06	2.9E-06	*4.4E-06*	*4.8E-06*	*4.3E-06*	*9.3E-07*
Repose		4.7E-06	5.2E-06	5.7E-06		*5.2E-06*	*5.2E-06*	*5.2E-06*	*4.7E-07*
Volume	2.8E-06	4.4E-06	4.9E-06	5.4E-06	3.4E-06	*4.5E-06*	*4.6E-06*	*4.5E-06*	*1.1E-06*
Minimum		4.0E-06	4.6E-06	5.2E-06	2.2E-06	*4.0E-06*	*4.3E-06*	*3.8E-06*	*1.3E-06*
Maximum		5.3E-06	5.7E-06	6.1E-06	4.5E-06	*5.4E-06*	*5.5E-06*	*5.5E-06*	*6.7E-07*
Ho (1992)	7.0E-06								
Mean	*4.4E-06*	*4.5E-06*	*5.0E-06*	*5.5E-06*	*3.6E-06*				
Median	*4.8E-06*	*4.5E-06*	*5.0E-06*	*5.5E-06*	*3.6E-06*				
Geomean	*4.3E-06*	*4.5E-06*	*5.0E-06*	*5.5E-06*	*3.5E-06*				
Std Deviation	*8.8E-07*	*3.8E-07*	*3.1E-07*	*2.5E-07*	*8.4E-07*				

Simulations 1 - 4: Trigen distribution. Simulation 1: min- max from Tables 7.5 and 7.6. Simulations 2-4: min-max from Fig. 7.11
Simulations 5: Normal distribution. Median and standard deviation from Tables 7.5 and 7.6.

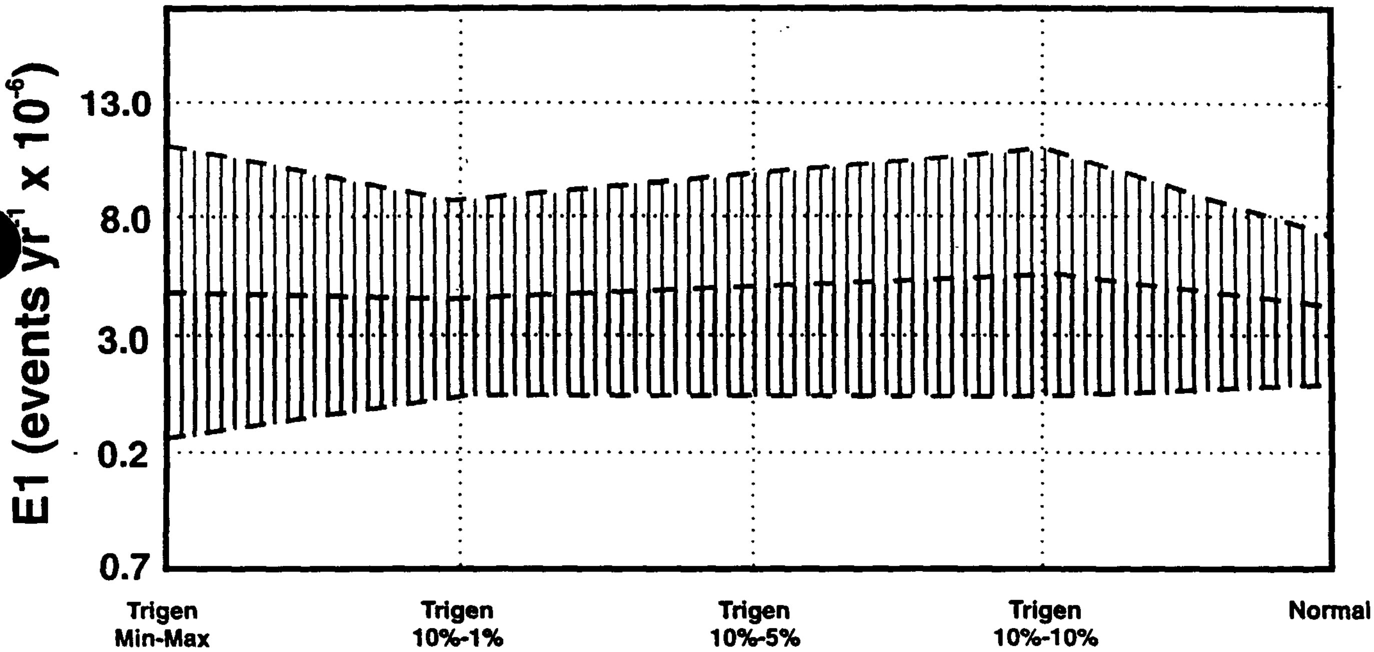
Simulated Results: E1



Expected Values:

Homogeneous 5.0E^{-6}
Nonhomogeneous 4.8E^{-6}
Repose 5.2E^{-6}
Volume 4.9E^{-6}
Minimum 4.6E^{-6}
Maximum 5.7E^{-6}
Ho(1992) 7.0E^{-6}

Risk Simulation: Homogeneous Poisson



Top ---- 90 per %

Center ---- 50 Per %

Bottom ---- 10 per %

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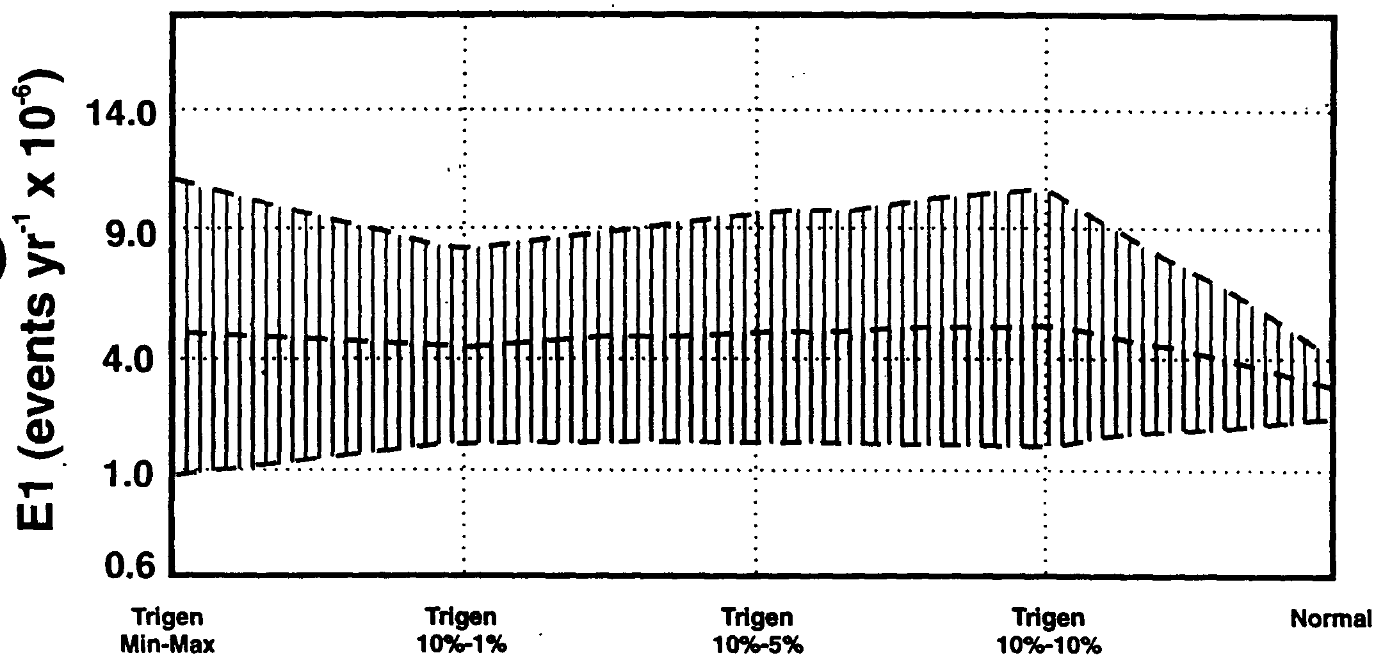
Risk Simulation: Nonhomogeneous Poisson

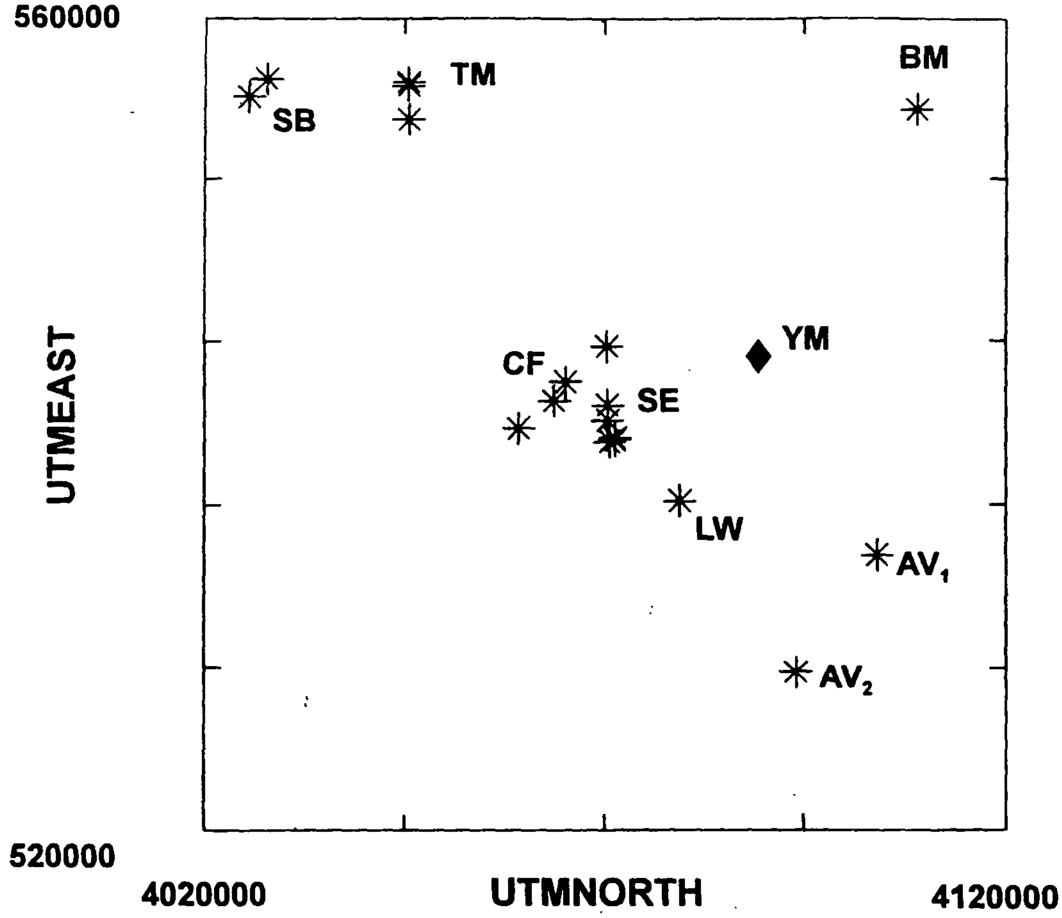


Top ---- 90 per %

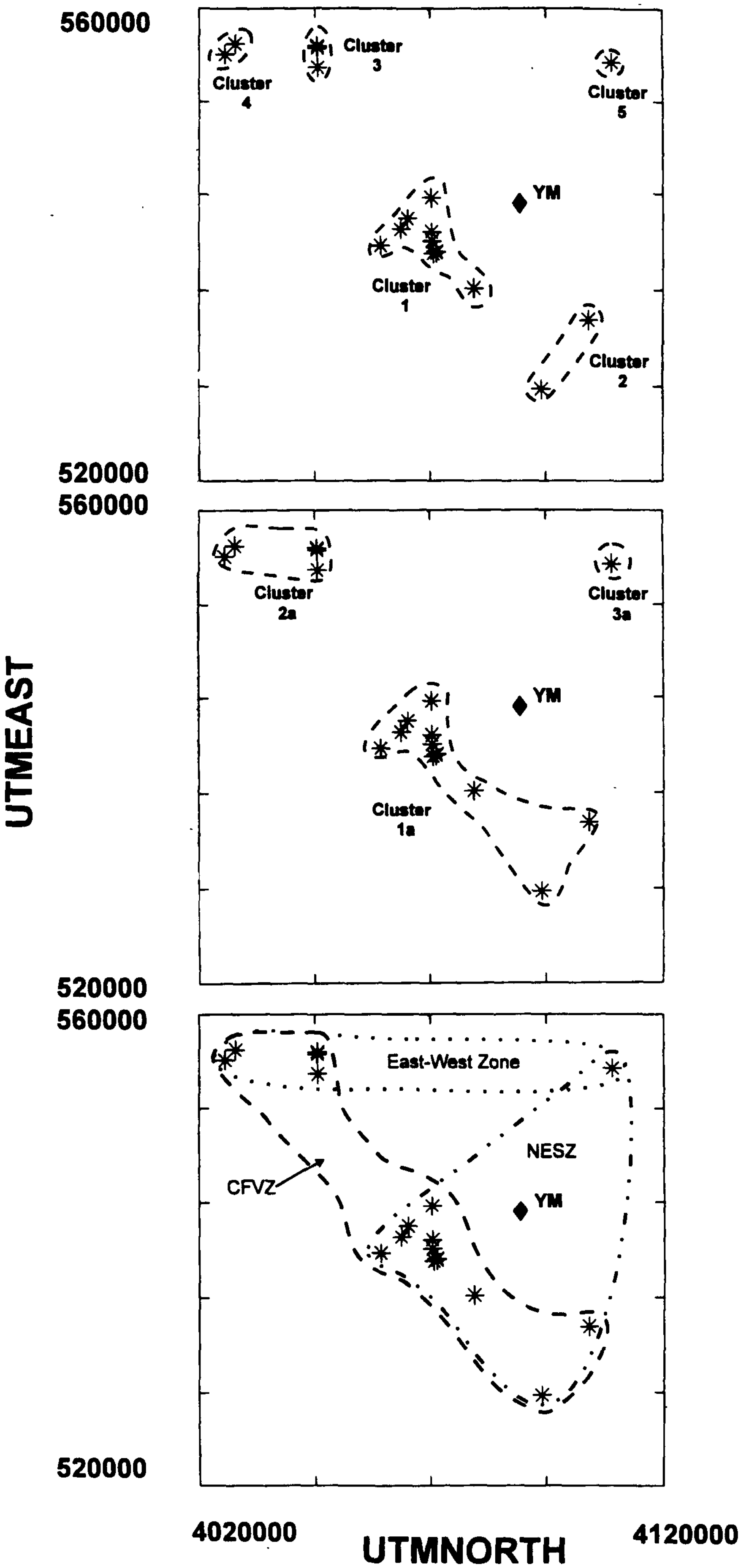
Center ---- Mean

Bottom ---- 10 per %

CRWNWTB.P2.CDR.123/2-28-94



560000
520000
UTMEAST
4020000
UTMNORTH
4120000
SB
TM
BM
YM
CF
SE
LW
AV1
AV2



560000
Cluster
4
Cluster
3
Cluster
5
YM
Cluster
1
Cluster
2
520000
560000
Cluster
2a
Cluster
3a
YM
Cluster
1a
520000
560000
East-West Zone
NESZ
CFVZ
YM
520000
UTMEAST
4020000
UTMNORTH
4120000

Table 7.13. Spatial Distribution Models for E2. Model 1 = Random, Model 2 = Range Interior, Model 3 = Range Interior + Range Front

Spatial Model	Time (Ma)	Area (km2)	Model 1	Model 2	Model 3	Comments
Quat Centers (circle)	1.00	2400	2.5E-03	3.7E-04	6.2E-04	Crowe et al. 1982
Quat Centers (ellipse)	1.00	4400	1.4E-03	2.0E-04	3.4E-04	Crowe et al. 1982
Quat + BB (circle)	3.75	2500	2.4E-03	3.6E-04	6.0E-04	Crowe et al. 1982
Quat + BB (ellipse)	3.75	2000	3.0E-03	4.5E-04	7.5E-04	Crowe et al. 1982
Cluster 1*	3.75	400	1.5E-02	2.2E-03	3.7E-03	Crater Flat Volcanic Field*
Cluster 2	3.85					Intersection not possible
Cluster 3	4.80					Intersection not possible
Cluster 4	4.80					Intersection not possible
Cluster 5	2.90					Intersection not possible
Cluster 1a*	3.75	750	8.0E-03	1.2E-03	2.0E-03	Crater Flat + Amargosa*
Cluster 2a	4.80					Intersection not possible
Cluster 3a	2.90					Intersection not possible
CFVZ	4.80	1450	4.1E-03	6.2E-04	1.0E-03	Crater Flat Volcanic zone
NESZ	3.85	1200	5.0E-03	7.5E-04	1.2E-03	Northeast Structural Zone
East-west zone	4.80					Intersection not possible
Cluster 1	1.00					Intersection not possible
Cluster 2	1.00	110				Lathrop Wells cluster
Cluster 3	1.00					Intersection not possible
Cluster 1a*	1.00	400	1.E-02	2.2E-03	3.7E-03	Quaternary CF + Lathrop*
Cluster 2a	1.00					Intersection not possible
CFVZ	1.00	1310	4.6E-03	6.9E-04	1.1E-03	Crater Flat Volcanic Zone
NHPP Cluster	3.75		2.0E-03	3.0E-04	5.0E-04	Connor and Hill
NHPP Cluster	3.75		2.4E-03	3.6E-04	6.0E-04	Connor and Hill
NHPP Cluster	1.00		2.7E-03	4.0E-04	6.7E-04	Connor and Hill
NHPP Cluster	1.00		3.1E-03	4.6E-04	7.7E-04	Connor and Hill
	Summary Statistics	***Mean***	***5.1E-03***	***7.6E-04***	***7.6E-04***	
		Median	***3.1E-03***	***4.6E-04***	***7.6E-04***	
		Std Dev	***4.5E-03***	***6.8E-03***	***1.1E-03***	
		Skew	***1.8***	***1.8***	***1.8***	
	(unlikely cases excluded)	***Mean***	***3.0E-03***	***4.5E-04***	***7.5E-04***	
		Median	***2.6E-03***	***3.9E-04***	***6.5E-04***	
		Std Dev	***1.2E-03***	***1.8E-04***	***2.9E-04***	
		Skew	***0.6***	***0.6***	***0.6***	

*** Spatial models noted by the asterisk are included in the first group of summary statistics but repository intersection is judged to be unlikely from geometrical constraints on the propagation of dikes from the cluster areas, and the long 1/2 length of projected dike dimensions required to achieve intersection.**

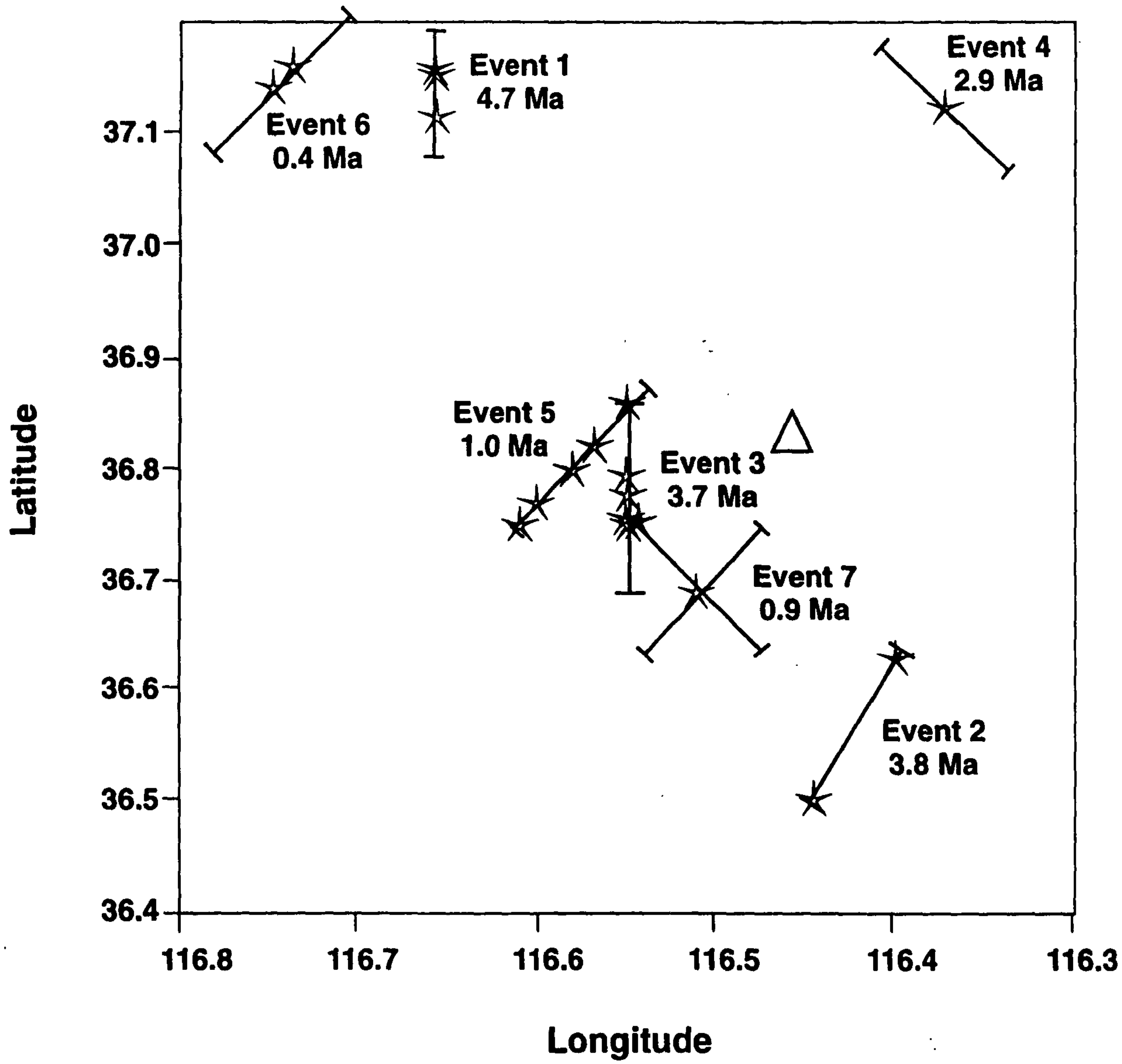


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Table 17.14. Alternative Structural Models for the Distribution of Pliocene and Quaternary Volcanic Centers in the YMR.

Structural Model	Evidence for Model	Evidence Against Model	Subsets or Alternative Models
Model 1: Crater Flat Volcanic Zone (Quaternary). This structural model is based on the definition of the Crater Flat volcanic zone of Crowe and Perry (1989). The dimensions of the zone are defined from the distribution of Quaternary volcanic centers.	*Supportive Evidence: northwest-trending linear distribution of volcanic vents, coincidence of the zone and vent alignment with the orientation of the surface of maximum eruption volumes, predominance of northwest structural trends in the Walker Lane structural zone, possible evidence of strike-slip offset of structural features in Paleozoic rocks, strike-slip pull-apart origin of Crater Flat.*	**Negative Evidence:** small number of volcanic centers, distance of gap between Crater Flat and Sleeping Butte centers, secondary northeast alignment of vent clusters.	***Alternative Submodels:*** *The Crater Flat centers and the Sleeping Butte centers may be located in separate structural zones.*
Model 2: Crater Flat Volcanic Zone (YPB). Same as model 1 but the dimensions of the zone are defined by the distribution of the Pliocene and Quaternary volcanic centers of the Younger Post-caldera basalt.	*Supportive Evidence: Same as Model 1.*	**Negative Evidence:** Same as model 1, basalt of Buckboard Mesa is not included in the structural zone.	***Alternative Submodels:*** *Same as Model 1, the aeromagnetic anomalies of the Amargosa Valley may also be in separate structural zones.*
Model 3: Yucca Mountain Region. This is a non-structurally based zone defined by the distribution of Pliocene and Quaternary basalt centers of the YMR. It is similar to but slightly larger than the Area of Most Recent Volcanism of Smith et al. (1990).	*Supportive Evidence: Model is based on the distribution of Pliocene and Quaternary volcanic centers in the YMR.*	**Negative Evidence:** No structural basis for model.	

Table 7.14 (cont)

Model 4: Crater Flat Volcanic field: This zone assumes that the major control of the occurrence of basalt centers is the local Crater Flat volcanic field, which is the primary site of Pliocene and Quaternary basaltic volcanism.	*Supportive Evidence: most of the Pliocene and Quaternary volcanic events have occurred in the Crater Flat basin, Crater Flat is the centroid of the distribution of units of the YPB, the Crater Flat basin may be a remaining area of active tectonism and maximum extension, Crater Flat basin was a site of Miocene basaltic volcanism.*	**Negative Evidence**: Other basalt centers occur outside the Crater Flat basin, the linear north-northwest alignment of basalt centers is oblique to the north-south elongation of the Crater Flat basin.	***Alternative Submodels**: Each group of volcanic rocks may record a separate volcanic field. These include the Crater Flat, Amargosa, Black Mountain and Buckboard fields.*
Model 5: Strike-Slip Structural Control: Model A. This structural model is based on the inference that the alignment of basalt centers parallels a concealed northwest-trending right-slip fault of the Walker Lane structural system. The model has been described by Schweickert (1989).	*Supportive Evidence: linear northwest alignment of basaltic volcanic centers, proposed offset of structural features of Paleozoic rocks, Walker Lane structural setting, clockwise rotation of field magnetization directions of the Tiva Canyon Member, coincidence of the basalt centers with zone of maximum rotation of the magnetization directions, similar structural bounds may be defined for Miocene basaltic volcanism (Older basalt of Crater Flat, aeromagnetic anomaly of VH-2).*	**Negative Evidence**: Strike-slip fault is not expressed at the surface, there is not always a strong correlation between strike-slips faults and sites of Quaternary volcanism in the basin-range.	***Alternative Submodels**: The Thirsty Mesa/Sleeping Butte centers and the aeromagnetic anomalies of the Amargosa Valley may be located on separate strike-slip faults and be unrelated to the Crater Flat basalt units.*

Table 7.14 (cont)

Model 6: Strike Slip Structural Control: Model B. This structural model is based on the inference that the south-southeast edge of the Crater Flat basin is bounded by a north-northwest trending, right slip fault. The Pliocene and Quaternary basalt centers are inferred to have ascended along this fault zone and diverted to the northeast (maximum compressive stress direction).	***Supportive Evidence:*** *steep gravity gradient paralleling proposed strike-slip fault, presence of north-northwest trending right-slip fault in the arcuate ridge at the south end of Crater Flat, clockwise rotation of field magnetization directions of the Tiva Canyon member, structural models of Crater Flat basin.*	**Negative Evidence**: Bare Mountain fault shows predominately dip-slip offset, basalt centers do not occur on the Bare Mountain fault, no correlation between volume of basalt centers and proximity to proposed bounding strike-slip fault.	***Alternative Submodels**: Same as model 5.*
Model 7: Stress-field Dike: Quaternary centers. This structural model assumes basalt magma ascended along a concealed structure defined by the northwest orientation of vents of the CFVZ. The feeder dike or dikes following this structure and diverted at shallow depths to follow the maximum compressive stress direction. The direction of dike propagation is either to the north-northeast or south-southwest.	***Supportive Evidence:*** *coincidence of the zone of maximum erupted volume of magma with the CFVZ, symmetrical distribution of vents about northwest-trending vent locations, cluster length of the Quaternary basalt of Crater Flat exceeds maximum likely dike length.*	**Negative Evidence**: multiple dikes are required only for the Quaternary basalt of Crater Flat, no recognized correlation between center chemistry and proposed dike systems, does not explain the distribution of all basalt centers.	***Alternative Submodels**: This model is a subset of the strike-slip models.*

Table 7.14 (cont)

Model 8: Stress-field Dike: Pliocene and Quaternary centers. This model is identical to model 7. The dimensions of the structural zone are defined by the distribution of Pliocene and Quaternary volcanic centers.	*Supportive Evidence: Same as model 8, aeromagnetic anomalies of Amargosa Valley may be analogous to the Quaternary basalt centers of Crater Flat, and formed basalt centers only at the ends of the dikes.*	**Negative Evidence**: Does not explain the occurrence of the basalt of Buckboard Mesa.	***Alternative Submodels**: May form three separate structural systems including the aeromagnetic anomalies of Amargosa Valley, the Crater Flat volcanic field, and the Thirsty Mesa/Sleeping Butte centers.*
Model 9: Chain model. Basalt centers follow northeast-trending chains and the chains form zones of higher risk for future volcanic events (Smith et al. 1990).	*Supportive Evidence: northeast-trends of clusters of contemporaneous volcanic centers, parallelism of northeast trends of clusters to bedrock faults of Yucca Mountain, analog comparison to other basaltic volcanic fields.*	Negative Evidence: risk zones are unsuccessful as predicators of future events, basalt of the YPB do not follow existing faults, dimensions of chains from analog volcanic fields exceed maximum cluster lengths of centers in the YMR, structural trends different for alignments of the Thirsty Mesa and basalt of southeast Crater Flat (north trending), longer chains occur only in alluvial basins, Lathrop Wells and Buckboard Mesa centers do not form chains, northeast trends are secondary to northwest trends.	

Table 7.14 (cont)

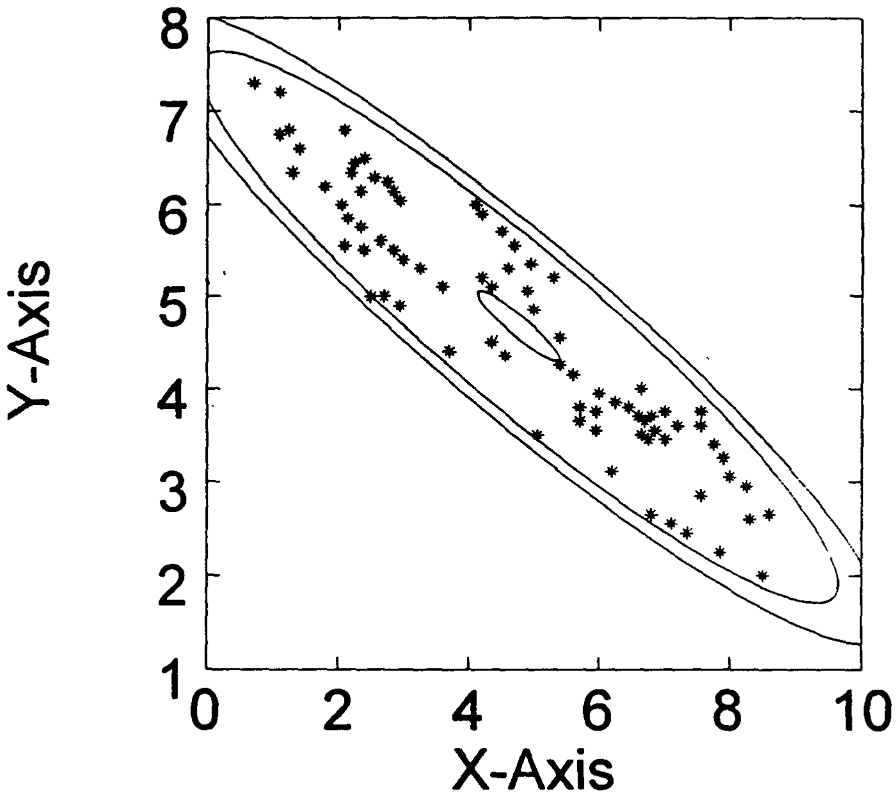
Model 10: Pull-Apart Basin: The Crater Flat basin is a pull-apart basin located at the termination of northwest-trending, strike-slip faults of the Walker Lane structural system. The basin is a tectonic basin and the basalt centers occur along extensional structures of the basin (Fridrich and Price 1992).	*Supportive Evidence: discontinuous northwest-trending faults of the Crater Flat area, multiple basalt cycles of the Crater Flat basin (10.5 Ma and Pliocene and Quaternary), gravity data showing steep, northwest-trending gradients, clockwise rotation of field magnetization directions of the Tiva Canyon Member, Walker Lane structural setting.*	**Negative Evidence**: the occurrence of basalt centers is not confined to the pull-apart basins, limited continuity of northwest-trending fault systems.	
Model 11: Caldera Model. The Crater Flat basin is a structural depression formed by multiple, coalesced caldera collapses associated with eruption of the Crater Flat tuff. Basalt centers are inferred to follow the ring-fracture system of the caldera complex (Carr, 1990).	*Supportive Evidence: Crater Flat basin is located on the south part of the southwest Nevada volcanic field, basalt centers are located commonly along ring-fracture zones of caldera complexes, basalt of Buckboard mesa is located on the ring-fracture of the Timber Mountain caldera, dike of Solatario Canyon and extensions may follow ring-fracture zone.*	**Negative Evidence:** caldera origin of the basin is controversial, basalt centers occur beyond the confines of the Crater Flat basin, basalt centers occur across the caldera floor and resurgent dome and are not confined to the ring-fracture zone.	

Table 7.14 (cont)

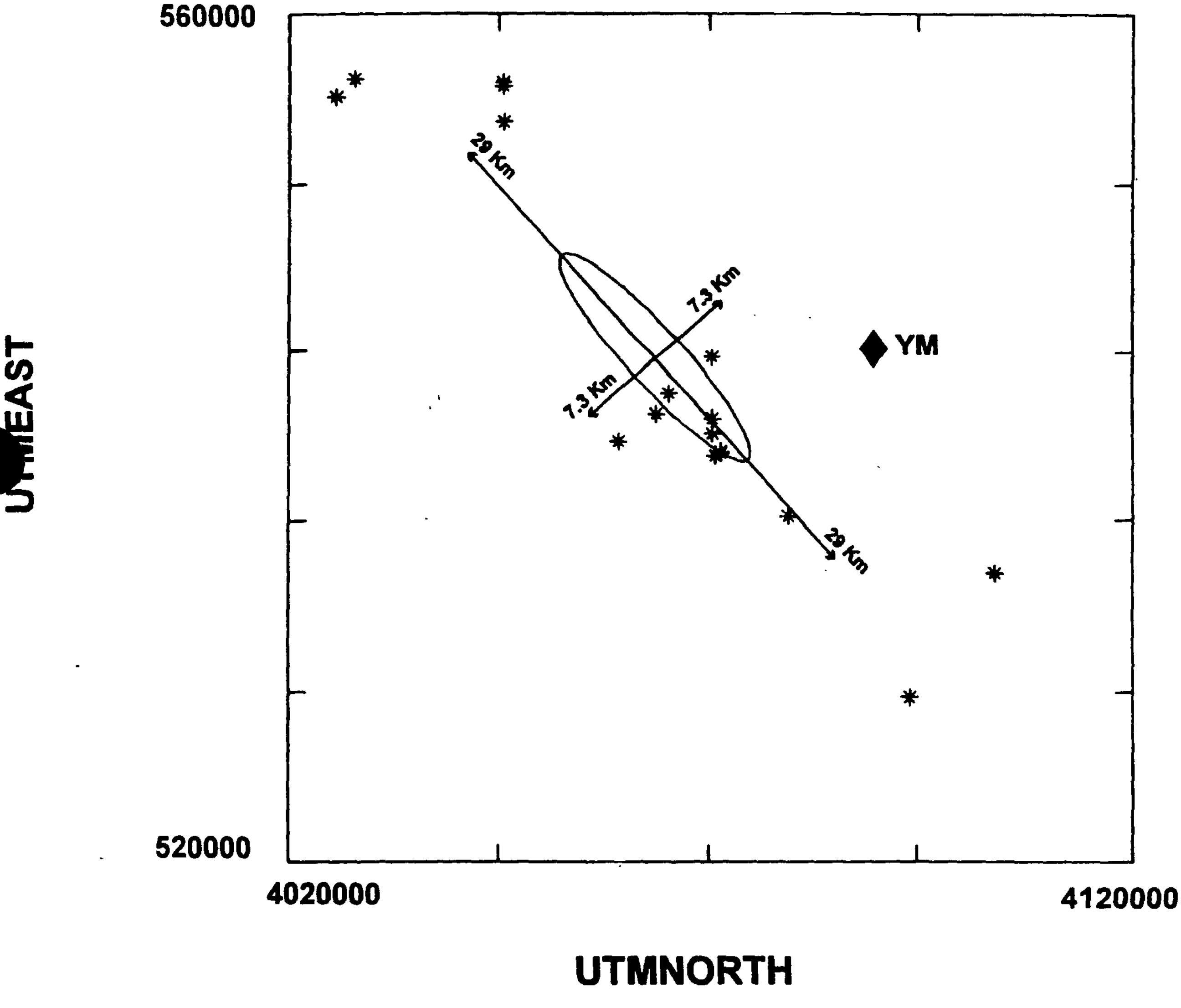
Model 12: Northeast Structural Zone: The YMR is located in a diffuse northeast trending, tectonic-volcanic rift zone. Sites of basaltic volcanism are more common in the zone than outside the zone; composite model proposed by Carr (1984; 1990; Kawich-Greenwater Rift zone, and Wright 1989; Amargosa Desert Rift zone).	*Supportive Evidence: northeast-trending zone of closely spaced, normal faulting, orientation of caldera centers in the southwest Nevada volcanic field, northeast trending structural trough that is delineated partly by gravity data, concentration of basaltic volcanic centers in the northeast-trending structural zone.*	**Negative Evidence:** structural zones may be a composite of multiple different structures, basalt centers are present both in and outside the structural zone, northwest linear alignment of basalt centers occur within the northeast-trending zone.	
Model 13: Crater Flat and Buckboard Mesa volcanic zone: The basalt centers of Crater Flat and the basalt of Buckboard Mesa form a northeast trending zone that extends through the potential Yucca Mountain site (proposed by Smith et al. 1990 and Naumann et al. 1992).	*Supportive Evidence: local northeast trends of basalt vents in Crater Flat, existence of the basalt centers of Crater Flat, and Buckboard Mesa.*	**Negative Evidence:** Distance of separation between the Crater Flat basalt centers and the basalt of Buckboard Mesa, interruption of the northeast-trends by oblique structures of the Timber Mountain-Oasis Valley caldera complex, northwest-trending vent alignments of the basalt of Buckboard Mesa, no basalt centers between Crater Flat and Buckboard Mesa.	

Table 7.15. Estimations of E2 for Structural Models of the Yucca Mountain Region.

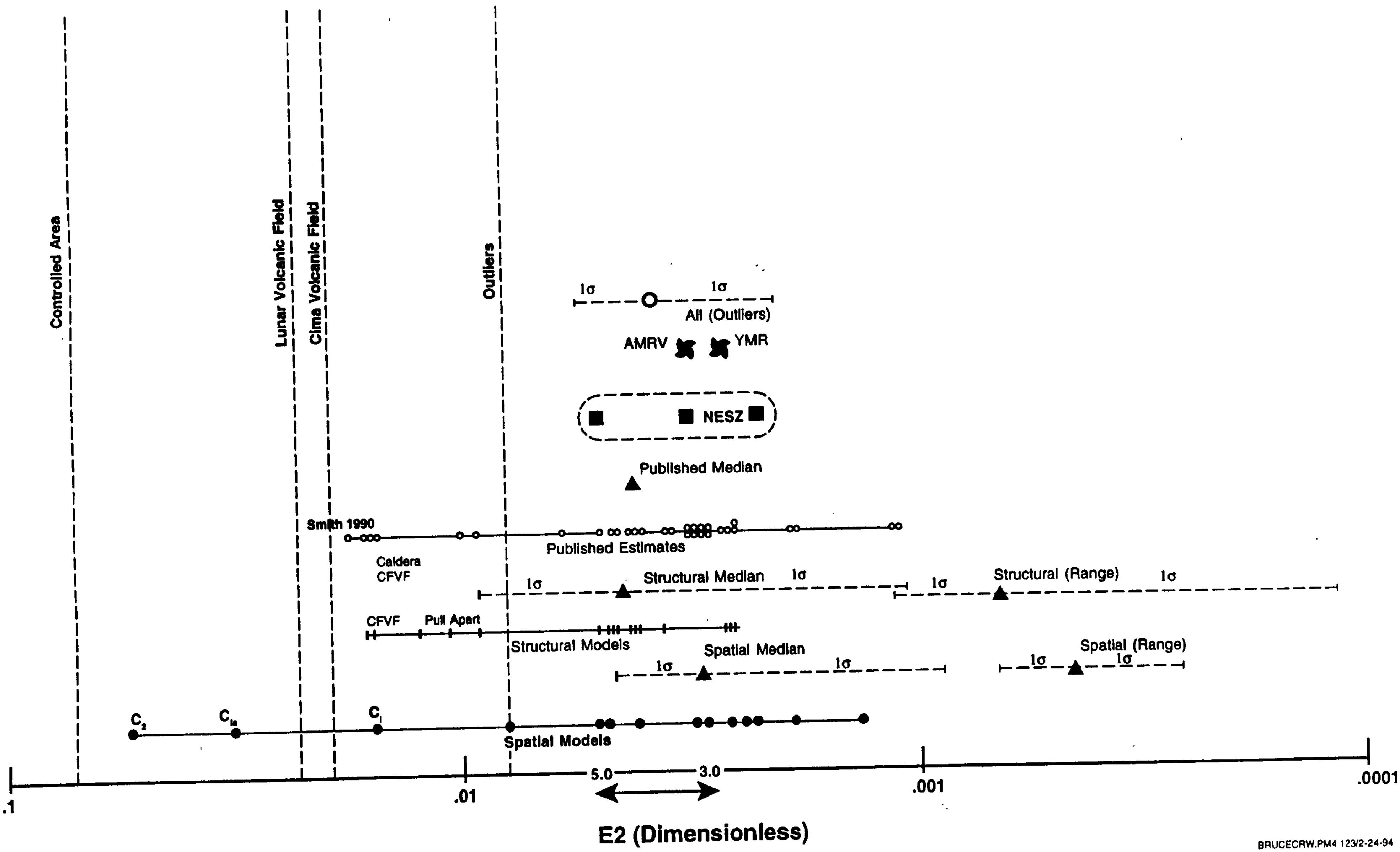
Model Number	Name	Time Interval	Intersection repository	Area (km^2)	Forced Intersection	Likelihood Intersection	E2 Intersection	E2 Interior	E2 Front
Model 1	CFVZ	1.00	no	1100	1310	Low	4.6E-03	6.9E-04	1.2E-03
Model 2	CFVZ	3.85	no	1350	1450	Low	4.1E-03	6.2E-04	1.0E-03
Model 3	YMR/AMRV	4.80	yes	2180	2180	High	2.7E-03	4.1E-04	6.9E-04
Model 4	CFVF	3.75	no	220	400	Unlikely	1.5E-02	2.2E-03	3.7E-03
Model 4a	CFVF with AV	3.85	no	750	750	Unlikely	8.0E-03	1.2E-03	2.0E-03
Model 5	Strike Slip	1.00	no	1100	1310	Low	4.6E-03	6.9E-04	1.1E-03
Model 6	Strike Slip	4.80	no	1350	1450	Low	4.1E-03	6.2E-04	1.0E-03
Model 7	Stress-Dike	1.00	no	1100	1310	Low	4.6E-03	6.9E-04	1.1E-03
Model 8	Stress-Dike	4.80	no	1350	1450	Low	4.1E-03	6.2E-04	1.0E-03
Model 9	Chain Model	3.75	no	390	450	Low	2.7E-03	4.0E-04	6.7E-04
Model 9a	Chain Model	3.85	no	500	690	Low	7.8E-04	1.2E-04	2.0E-04
Model 10	Pull-Apart	3.75	no	390	450	Unlikely	1.3E-02	2.0E-03	3.3E-03
Model 10a	Pull-Apart	3.85	no	500	690	Unlikely	8.7E-03	1.3E-03	2.2E-03
Model 11	Caldera	3.75	no	220	400	Moderate	1.5E-02	2.2E-03	3.7E-03
Model 12	Kawich Rift	3.75	yes	1700	1700	High	3.5E-03	5.3E-04	8.8E-04
Model 12a	12 with AV	3.85	yes	2250	2250	High	2.7E-03	4.0E-04	6.7E-04
Model 13	NESZ	3.75	yes	1200	1200	High	5.0E-03	7.5E-04	1.2E-03
				Statistics	***(all models)***	***Mean***	***6.1E-03***	***9.1E-04***	***1.5E-03***
						Median	***4.6E-03***	***6.9E-04***	***1.1E-03***
						Geomean	***4.8E-03***	***7.2E-04***	***1.2E-03***
						StdDev	***4.4E-03***	***6.6E-04***	***1.1E-03***
				Statistics	***(intersection models)***	***Mean***	***3.5E-03***	***5.2E-04***	***8.7E-04***
						Median	***3.1E-03***	***4.7E-04***	***7.8E-04***
						Geomean	***3.4E-03***	***5.0E-04***	***8.4E-04***
						Std Dev	***1.1E-03***	***1.6E-04***	***2.7E-04***



8
7
6
5
4
3
2
1
0
2
4
6
8
10
Y-Axis
X-Axis



560000
520000
4020000
4120000
UTMEAST
UTMNORTH
29 Km
29 Km
7.3 Km
7.3 Km
YM



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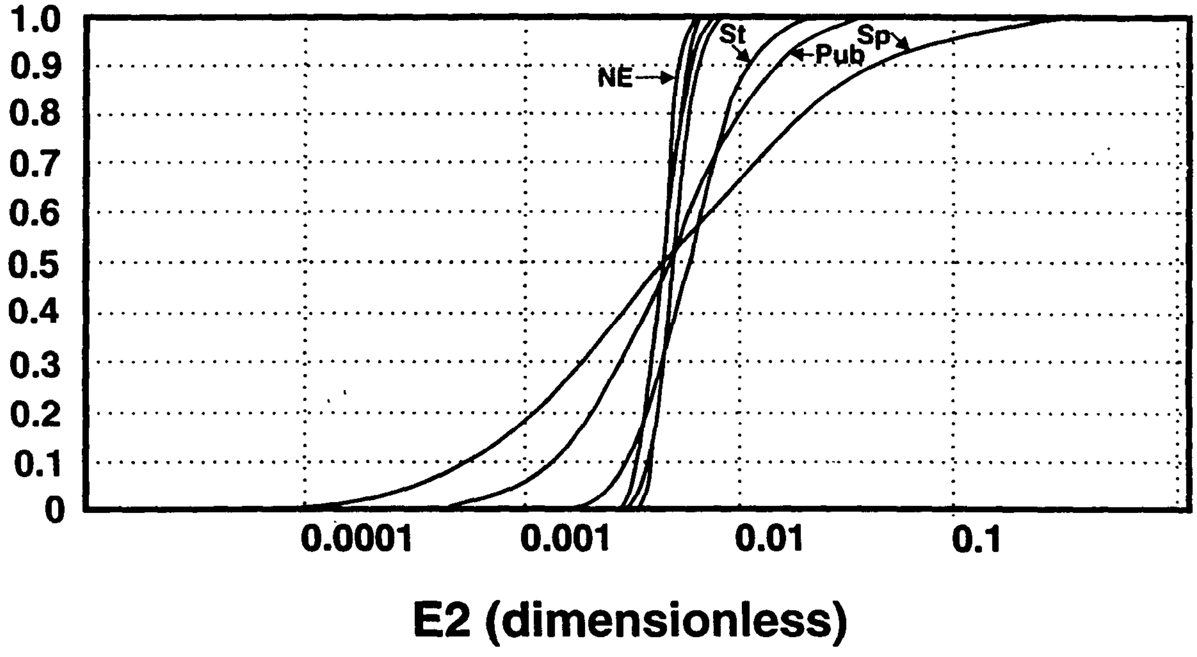
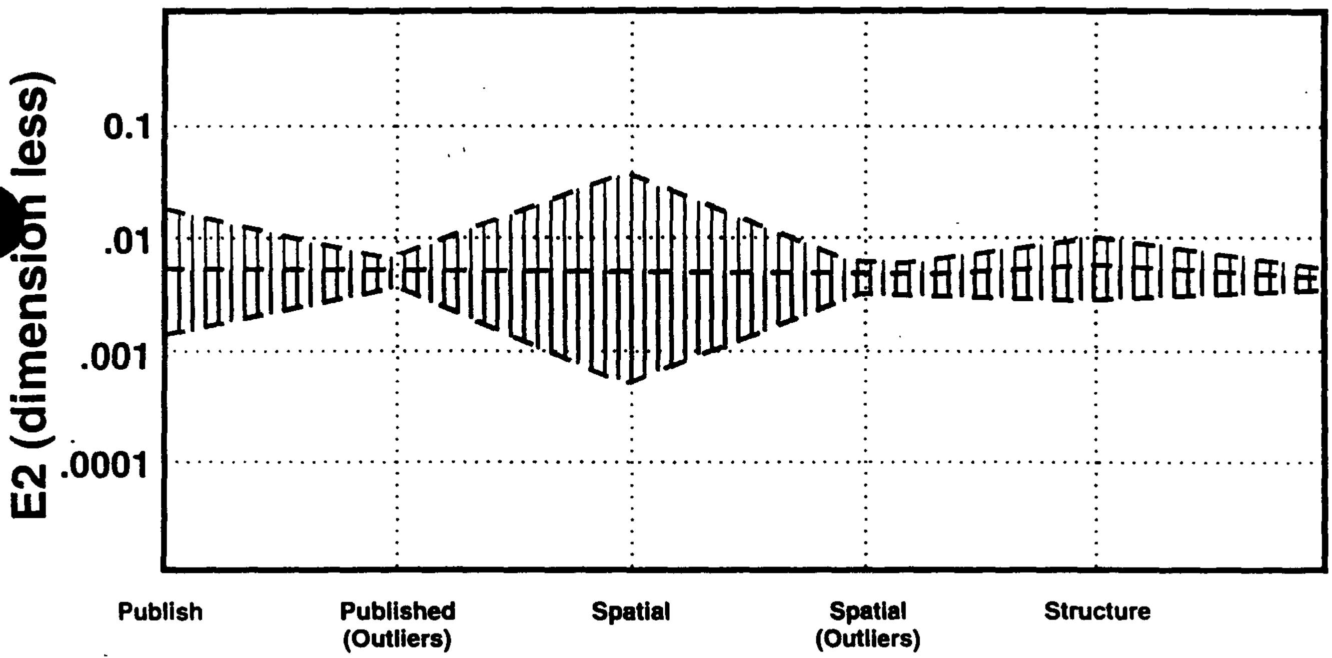
Simulation Results: E2



Expected Value

All Published $4.1E^{-3}$
Published (outliers) $3.8E^{-3}$
All Spatial $3.1E^{-3}$
Spatial (outliers) $2.8E^{-3}$
Structural $4.6E^{-3}$
NE Trend $3.1E^{-3}$

Risk Summary: E2intersect



Top ---- 90 per %

Center ---- Mean

Bottom ---- 10 per %

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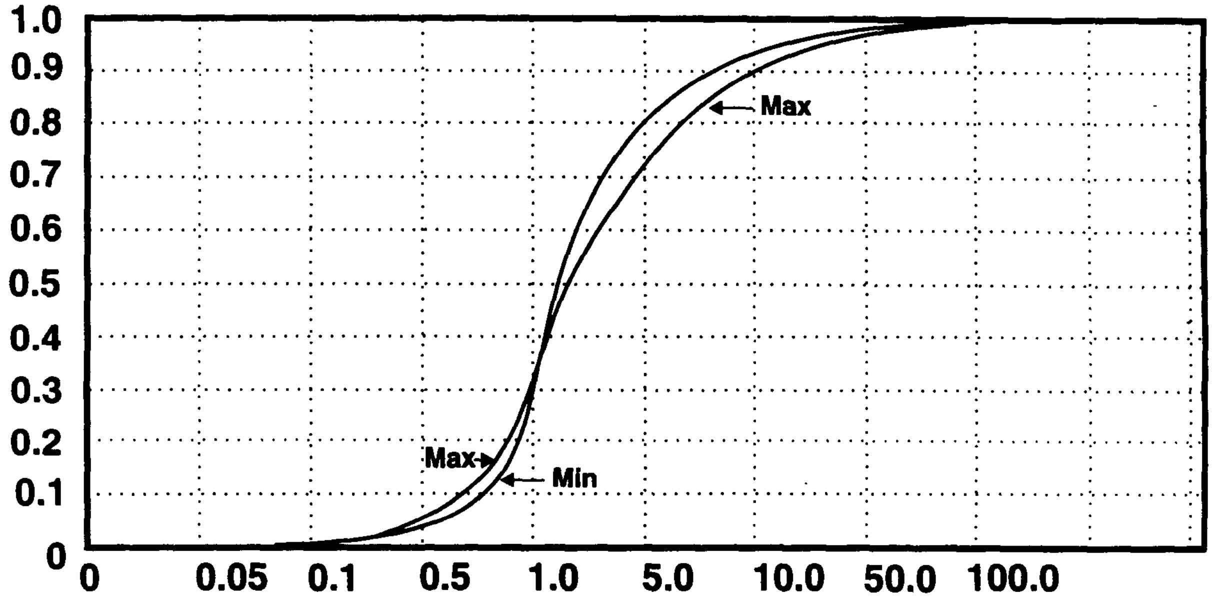
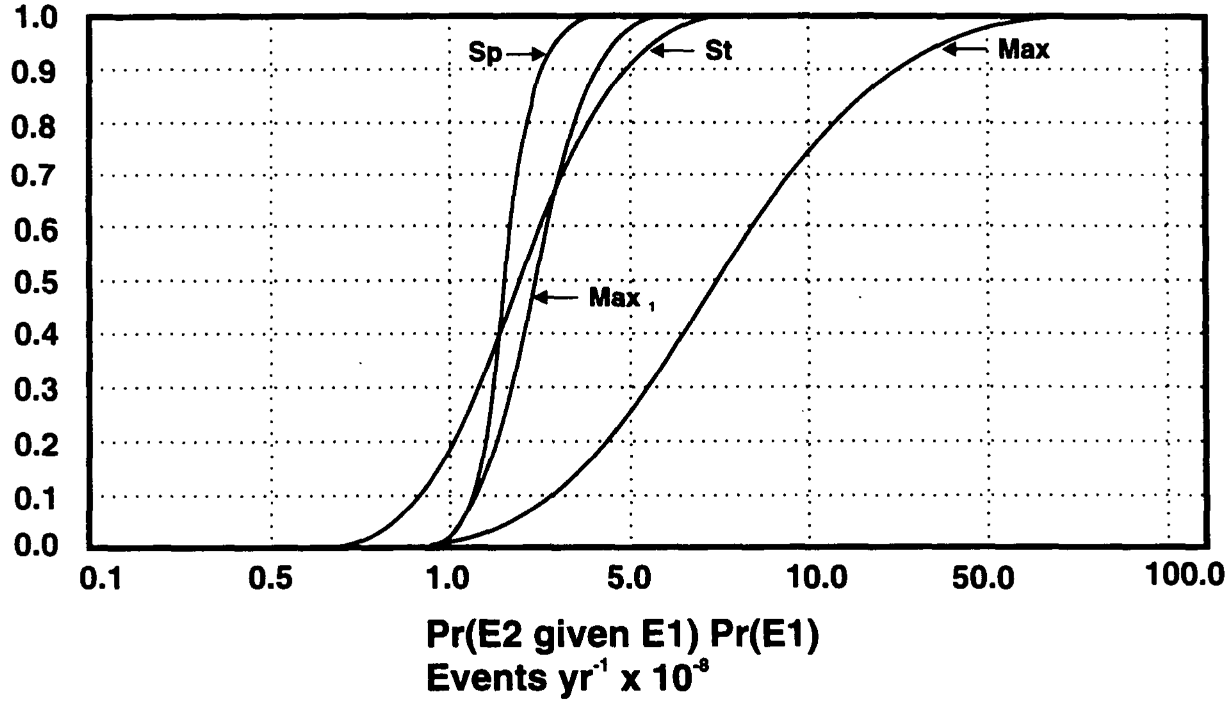
Simulation Results: E2 Fixed



Pr(E_2 given E1)Pr(E1)
Events yr^{-1} x 10^{-8}

Simulation Results: Intersection Models



Expected Value

Structural 2.25 x 10^{-8}
Spatial 1.5 x 10^{-8}
Maximum 7.3 x 10^{-8}
Maximum 2.4 x 10^{-8}
(outliers)

Table 7.23. Probability of magmatic disruption of the repository where the recurrence rate (E1) is adjusted for individual spatial and structural models of E2.

Spatial Models	E2	E1 Adjusted	Pr(E2 given E1)Pr(E1) Intersection	Z Score	Range
Cluster 1 (3.7)	*1.5E-02*	*2.6E-06*	*4.01E-08*	1.4	*6.0E-09*
Cluster 1a (3.85)	8.0E-03	2.3E-06	1.9E-08	0.0	2.8E-09
CFVZ (4.8)	4.1E-03	3.7E-06	1.5E-08	-0.1	2.3E-09
NESZ (3.85)	5.0E-03	3.6E-06	1.8E-08	0.0	2.7E-09
Cluster 1a (1.0)	*1.5E-02*	*5.0E-06*	*7.5E-08*	3.6	*1.1E-08*
CFVZ (1.0)	4.6E-03	6.0E-06	2.7E-08	0.6	4.1E-09
Structural Models					
CFVZ (1.0)	4.6E-03	6.0E-06	2.7E-08	0.6	4.1E-09
CFVZ (4.8)	4.1E-03	2.5E-06	1.0E-08	-0.5	1.5E-09
YMR (4.8)	2.7E-03	2.5E-06	6.9E-09	-0.7	1.0E-09
CFV Field (3.75)	1.5E-02	1.6E-06	2.4E-08	0.4	3.6E-09
CFV Field + AV	8.0E-03	2.3E-06	1.9E-08	0.0	2.8E-09
Strike Slip (1.0)	4.6E-03	6.0E-06	2.7E-08	0.6	4.1E-09
Strike Slip (4.8)	4.1E-03	2.3E-06	9.5E-09	-0.5	1.4E-09
Stress-Dike (1.0)	4.6E-03	2.7E-06	1.2E-08	-0.4	1.8E-09
Chain Model (3.7)	2.7E-03	1.6E-06	4.3E-09	-0.9	6.4E-10
Chain Model (3.85)	7.8E-04	2.1E-06	1.6E-09	-1.0	2.4E-10
Pull-Apart (3.7)	1.3E-02	1.6E-06	2.1E-08	0.2	3.2E-09
Pull-Apart (3.85)	8.7E-03	2.1E-06	1.8E-08	0.0	2.7E-09
Caldera (3.75)	1.5E-02	1.6E-06	2.4E-08	0.4	3.6E-09
Kawich Rift (3.7)	3.5E-03	1.6E-06	5.6E-09	-0.8	8.5E-10
Kawich Rift (3.85)	2.7E-03	2.1E-06	5.5E-09	-0.8	8.3E-10
NESZ (3.7)	5.0E-03	1.9E-06	9.4E-09	-0.6	1.4E-09
	Summary Statistics	*Mean*	*1.9E-08*		*2.9E-09*
		Median	*1.8E-08*		*2.7E-09*
		Geomean	*1.5E-08*		*2.2E-09*
		StDev	*1.6E-08*		*2.1E-09*
		Skewness	*2.2*		*2.2*
		Minimum	*1.6E-09*		*2.4E-10*
		Maximum	*7.5E-08*		*1.1E-08*

What Have We Learned
Probability Estimates

1. Recurrence Models: well constrained

    insensitive to mid-point estimates
    boundary assumptions far more important

How much could they Change?
    undetected intrusions
    undetected centers

    Factor of 2 or 3 to be significant

14 to 21 *undetected* centers or intrusions

2. Structural Models

    small number of structural/spatial models are significant
        dike lengths
        structural models
        Geophysics/field studies may be useful
        Pliocene or Quaternary dikes in exploration block
    Northeast-trending models are not sensitive

Judgment required: suitability of high probability disruption ratios

3. Effects Studies are Needed

    Controlled Area
    Yucca Mountain Region
    Repository (dependent on range interior models)

Judgment required: suitability of models
criterion on probability distribution curve

Future Directions
Probability/Volcanism Studies

1. Examination of Polycyclic Models/Probability Estimates

   High E1, very low E2, probable very very low E3

   "Standoff" distance being assessed for subsurface effects

2. Geophysical Studies

   Magma bodies
   Test structural models
   Subsurface geometry: small volume basalt centers
   Undetected features (but is this significant?)

3. Evolutionary Patterns of Volcanic Fields

   Test assumptions of probability models

4. Yearly Updates: Probability Estimates

   Sensitivity to site characterization
   Simulation Framework Established: Revisions relative easy

5. Importance of Expert Judgment