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July 13, 1988

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Dear Mrs. Brooks:

Enclosed is the final draft of "Techniques for Determining Probabilities of Events and Processes Affecting the Performance of Geologic Repositories: Volume I--Literature Review" which is currently going through management approval at Sandia. Since the report is, for all practical purposes, complete, the agreed deadline for completion has been met.

Sincerely,

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TECHNIQUES FOR DETERMINING PROBABILITIES OF EVENTS AND PROCESSES AFFECTING THE PERFORMANCE OF GEOLOGIC REPOSITORIES:

VOLUME 1--LITERATURE REVIEW

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May 1988

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ABSTRACT

The US Environmental Protection Agency (EPA) has set a probabilistic standard for the performance of geologic repositories for the disposal of radioactive waste. The EPA has not suggested ways to determine probabilities of events and processes of interest in implementing such a standard, but Appendix B of the standard states that numerical and analytical methods and expert judgment are probably all acceptable. This report treats not only geologic events and processes like fault movement, but also events and processes that arise from the relation between human actions and geology, like drilling for resources, and some that arise from non-geologic processes that in turn affect a geologic process, like climatic change. It reviews the literature in several fields to determine whether existing probabilistic methods for predicting events and processes are adequate for implementation of the standard.

Techniques exist for qualitatively estimating the potential for endowment of portions of Earth's crust with mineral resources, but such techniques cannot easily predict whether or not human intrusion will occur. The EPA standard offers explicit guidance for the treatment of human intrusion, however. A complete method for climatic prediction could be assembled from existing techniques, although such a combination has not been tested. Existing techniques to support a probabilistic assessment of tectonic activity and seismic hazard at a repository site should be combined with expert judgment in performance assessments. Depending on the regional setting, either analytic techniques or expert judgment may be appropriate in assigning probabilities to volcanic activity.

TABLE OF CONTENTS

	Page
FOREWORD	xx
ACKNOWLEDGMENTS	xxi
EXECUTIVE SUMMARY	1
1. INTRODUCTION	21
Abstract	21
General Discussion	21
Using Probabilities in Performance Assessment	23
Goals of this Study	24
Regulatory Background	26
Role of Probabilistic Calculations in the Regulatory Process	26
Project Approach	28
Methods of Determining Probabilities	31
Estimating Probabilities of Geologic Events and Processes	35
Objective Probability Estimates from Empirical Distribution Functions	35
Empirical Distribution Functions	36
Fitting Curves to EDF Data	38
Theoretical Distribution Functions	38
Objective Probabilities without Distribution Functions	38
Elimination by Consequence Analysis or Bounding	39
Subjective Probability Methods	39
Analysis of Uncertainties	40
Methods for Combining Uncertainties	41
Monte Carlo	41
Maximus	41
Adjoint	42
Factorial Designs	42
Bayesian	42
Summary	43
References	44

TABLE OF CONTENTS (continued)

		Page
2.	RESOURCE EXPLORATION	51
	Abstract	51
	Introduction	51
	Regulatory Guidance	52
	The Basic Tree of Interdependent Probabilities	53
	The Repository's Probability Envelope	57
	Consideration of Future Economics and Exploitability Versus Depth	62
	Estimating Conditional Probabilities for Specific Mineral Commodities	66
	Estimating Probabilities for All Commodities Combined	68
	Probability of Intersection of Probability Envelope in Exploratory Drilling	69
	Sources for Frequency Distribution of Specific Commodities or Categories of Commodities Expressable on a Unit-Area Basis	71
	Oil and Gas	71
	Metals	73
	The Unit-Regional Value Approach	74
	How Much Exploratory Drilling Should be Expected?	76
	Summing Up the Literature: Are Procedures and Data Available for the Task?	77
	Data Bases Pertaining to Mineral Commodities	77
	Procedures for Estimating Probabilities of Intersecting Deposits by Boreholes	78
	Procedures for Assessing Undiscovered Resources	79
	Conclusions	81
	Discussion of Currently Available Approaches	83
	Acknowledgments	84
	References	84

TABLE OF CONTENTS (continued)

	Page
3. CLIMATOLOGY	89
Abstract	89
Introduction	89
Components of the Climate System	91
Basic Components	91
Controls of Climatic Variations	91
Temporal and Spatial Scales of Climatic Variability	93
Temporal Variations	93
Spatial Variations	93
Climate Prediction	93
Classes of Climate Prediction	93
Climate Prediction at Different Time Scales	95
Potentially Predictable Events and Processes	96
Climatic Variations on the Quaternary Time Scale	96
Focus of This Chapter	97
Methods of Climate Prediction for 10^4 Years	98
Paleoclimatic-Data-Based Predictions	98
Predictions Based on Descriptive Studies	98
Predictions Based on Statistical Analyses	98
Climate-Model-Based Predictions	102
Models of the Fast-Response Components	102
Models of the Slowly Varying Components	106
Summary	108
Critical Analysis of Prediction Methods	108
An Approach to Long-Term Prediction	108
Prediction of Slowly Varying Components	111
Prediction of Fast-Response Components	111
Implementation of a Prediction Strategy	112
Model Selection	112
Model Validation	113
Summary	114
Availability of Data Bases for Climate Prediction	114
Phenomena Not Currently Predictable	115
Climate Prediction Performance Assessment	116
Discussion of Currently Available Approaches	116
Acknowledgments	117
Appendix 3.1	117

TABLE OF CONTENTS (continued)

Page

Appendix 3.2 121

References 123

4. TECTONICS AND SEISMICITY 130

Abstract 130

Introduction 131

Methods 133
- Rupture of Land Surface 133
  - Fault Recurrence 133
    - Method 133
    - Results 133
    - Data 134
    - Limitations 134
    - Assessment 134
  - Dating Techniques for Quaternary Deposits 134
    - Radiometric Dating 134
    - Other Quantitative Numerical Techniques 135
    - Relative Age Dating 137
    - Assessment 137
  - Types of Quaternary Features Used for Recurrence Studies 138
    - Stratigraphic Sequences: Quaternary Sedimentary Deposits 138
    - Other Stratigraphic Indicators: Landforms and Stratigraphic Features Inferred to Reflect Earthquake Motions Related to Fault Rupture 138
    - Offset, Displaced, or Anomalous Landforms 138
    - Assessment 139
  - Stream-Profile Analysis 140
    - Method 140
    - Results 140
    - Data 140
    - Limitations 140
    - Assessment 140
  - Fault-Scarp Morphology 140
    - Method 141
    - Results 141
    - Data 141
    - Limitations 143
    - Assessment 143
- Vertical Crustal Movements 143
  - Fluvial Adjustments 144
    - Method 144

TABLE OF CONTENTS (continued)

	Page
Results	144
Data	144
Limitations	145
Assessment	145
Regional Patterns of Dissection or Degradation	145
Method	145
Results	145
Data	145
Limitations	146
Assessment	146
Regional Denudation	146
Method	146
Results	146
Data	146
Limitations	146
Assessment	146
Anomalous Map-View Channel Patterns	146
Method	146
Results	147
Data	147
Limitations	147
Assessment	147
Marine and Lacustrine Terraces and Shorelines	147
Method	147
Results	147
Data	147
Limitations	148
Assessment	148
Correlation of Tectonics and Seismicity	148
Earthquake Prediction	148
Long-Term Precursors	148
Short-Term Precursors	149
Quantification and Models	149
Assessment	150
Fault Rupture and Seismicity	151
Method	151
Results	151
Data	151
Limitations	152
Assessment	152
Critical Comparison of Various Methods	152
Availability of Data Bases and Variables of Each	153
Tectonic Data	153
Seismic Data	154

TABLE OF CONTENTS (continued)

	Page
Phenomena Not Presently Predictable by Previously Discussed Methods	154
Regional State of Stress and Strain	154
Tectonic Processes	155
Tectonic Features	156
Assessment	156
Evaluation of Best Method for Performance Assessment	156
Discussion of Currently Available Approaches	158
Data	158
Implementation of Methods	158
Conclusions	158
References	158
5. SEISMIC HAZARD ASSESSMENT	180
Abstract	180
Seismic Hazard Integration	181
Recurrence Models	182
Standard Poisson Exponential Model	182
Description	182
Data Needs and Availability	183
Merits and Limitations	183
Models with Temporal Memory	184
Description	184
Data Needs and Availability	185
Merits and Limitations	185
Models with Temporal and Spatial Dependence	186
Description	186
Data Needs and Availability	186
Merits and Limitations	186
Ground Shaking	186
Direct Empirical Methods	189
Description	189
Data Needs and Availability	190
Merits and Limitations	191
Indirect Empirical Methods	191
Description	191
Data Needs and Availability	192
Merits and Limitations	192
Semi-Empirical Methods	192
Description	192
Merits and Limitations	193
Stochastic Methods	193

TABLE OF CONTENTS (concluded)

Page

Data Needs and Availability 194
Merits and Limitations 194
Deterministic Methods 195
Description 195
Data Needs and Availability 195
Merits and Limitations 195
Earthquake Faulting 195
Magnitude-Occurrence Models of Faulting 196
Description 196
Data Needs and Availability 197
Merits and Limitations 197
Faulting-Occurrence Models 198
Description 198
Data Needs and Availability 199
Merits and Limitations 199

Discussion of Currently Available Approaches 200

References 200

6. VOLCANOLOGY 213

Abstract 213

Introduction 213

Geological Background 214
Broad Continent-Wide Regimes 214
Tectonic Analyses of Structural Evolution 214
Analyses of Stress Distribution in Continental Plates 215
Potential Value for Probability Estimates 215
Global Distribution of Volcanism in Geologic Time 216
Regional Settings of a Single Geologic Province 216
Sources of Information on Regional Patterns of Volcanism 219
Specific Igneous Centers 220

Methods of Estimating Probabilities of Volcanic Hazards 221

Possible Interactions between Volcanic Processes and Waste Repository 227

Conclusions and A Currently Feasible Approach 230

References 231

FIGURES

Page

E-1. Bases for probabilities assigned to events and processes in the fields considered in this report 6

1-1. Example of an event tree containing several scenarios 25

1-2. A flowchart for dealing with events and processes whose probabilities cannot be determined 32

1-3. Four mathematical functions used in determining probabilities ... 37

2-1. Basic probability tree involving breaching versus not breaching of HLW repository by human activity 55

2-2. Second-stage probability tree diagram that extends branch (d) of Figure 2-1 56

2-3. Hypothetical probability envelope surrounding repository 58

2-4. Effect of setting depth limit for borehole such that borehole penetrates only part of envelope 60

2-5. Unit area onto which contours of probability envelope have been projected 61

2-6. Multiplicative roles of relative demand, exploitability/depth index, and conditional probability of commodity's occurrence .. 63

2-7. Hypothetical curves representing relative demand versus time 64

2-8. Hypothetical curves representing exploitability as a function of depth 65

2-9. Hypothetical diagram to illustrate probability distribution functions, for aggregates of commodities, that are conditional upon specific geological groups of rocks and their volumes, within unit area 67

2-10. Diagram to illustrate probability of repository being intersected on unit-area basis 70

2-11. Expanded tree dealing with events subsequent to drilling of boreholes in area of repository site 72

2-12. Overall tree combining elements show in Figure 2-1, 2-2, 2-6, and 2-11 82

FIGURES (continued)

Page

3-1. Principal components of the climate system and their interactions 92

3-2. General trends in global climate for various time scales ranging from 10^2 to 10^6 years 94

3-3. Past and predicted future variations of an ^{18}O series 100

3-4. Past and predicted future variations of composite records of pollen data from Lake Biwa 101

3-5. Simulated land-surface temperature and sea-level pressure differences between 9000 years B.P. and today 104

3-6. Simulated past and predicted future variations in zonal mean temperature (expressed as deviations from the modern values) .. 105

3-7. Orbital input and past and predicted future ice volumes simulated by the Imbrie and Imbrie (1980) model, and observed ^{18}O records 107

3-8. Plots of the astronomical climate index for the past and future 10^6 years 109

3-9. Global paleoclimatic data base for 6000 years B.P. 115

3-10. Relative rate of climatic change and transition probability 119

6-1. Relations between explosivity and time intervals between eruptions 219

6-2. Cumulative curves showing volcanic vents and loci active during specific time periods over the past 5 million years, exclusive of the Cascade zone 224

6-3. Wickman diagrams for three large volcanoes with long records of eruptive activity 227

6-4. Volcanic risk map for the area around Guadalajara, Mexico 229

6-5. A plot of the fraction of crystallization against dimensionless temperature 230

TABLE

		Page
3-1.	Characteristics of climate prediction methods	110

FOREWORD

The US Environmental Protection Agency (EPA) has set a standard for the release of radioactive waste from mined geologic repositories. This standard is probabilistic and risk-based, in that it allows certain releases at high probabilities and greater releases at lower probabilities. The EPA requires that probabilities be used in performance assessments that culminate to the extent practicable in the preparation of complementary cumulative distribution functions (ccdf's) that show the probability of exceeding any given release.

The US Nuclear Regulatory Commission (NRC) is responsible for implementing the EPA standard by licensing only those repositories whose performance assessments provide a reasonable expectation that the standard will be met. Therefore, it is essential that the NRC be in a position to prepare ccdf's and thus to judge the quality of any ccdf's and their contained probabilities that are presented to NRC during licensing proceedings.

In the past, no consensus has existed about the best ways to determine the probabilities of the many events and processes that will be considered during the preparation of a ccdf. For this reason, the NRC has undertaken the task of evaluating and selecting appropriate methods for determining these probabilities. The NRC has funded the Waste Management Systems Division at Sandia National Laboratories to carry out the work. This volume is the first of two that will present the results of this task.

Volume 1, this report, is a literature review. In preparing this volume, experts in various geologic and closely related fields were asked to compile techniques in use in their fields for probabilistic predictions and to evaluate the state of the art. The evaluations do not constitute endorsements; it is too early in the overall task for the NRC or Sandia to endorse one technique over another. Volume 2, to follow, will apply selected techniques to problems typical of repository performance assessments. At that time it may be possible to endorse certain probabilistic techniques for use in performance assessments to be submitted to the NRC during licensing proceedings.

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EXECUTIVE SUMMARY

Introduction

In 1985, the US Environmental Protection Agency published an environmental standard for the management and disposal of spent fuel and high-level and transuranic radioactive waste. The standard governs allowable releases from geologic repositories for the disposal of radioactive waste. The standard is probabilistic. It sets certain limits for contaminant releases that are estimated to have more than one chance in 10 of occurring within 10,000 years, and a less strict set of limits for releases estimated to have between one chance in 10 and one chance in 1000 of occurring within 10,000 years. Because the standard does not offer any guidelines for methods of determining probabilities, this report examines techniques for estimating probabilities. In Appendix B of its standard, the EPA explicitly assumes that a number of techniques will be appropriate for predicting the likelihood of events and processes that may disturb a repository. Complex computational models, analytical theories, and prevalent expert judgment are assumed to be appropriate techniques. In addition, the EPA assumes that, because of the uncertainties likely to be present, the NRC may choose to supplement predictions with qualitative judgments.

The NRC's waste-management regulations have been framed to provide reasonable assurance that the EPA's standard is met. Because the NRC staff has had a decade of experience with using probabilistic methods to support reactor-safety decision-making, the NRC has had an opportunity to consider just what role these methods can play and what their limitations are. In recent years, regulators have recognized that probabilistic analysis can offer a realistic description that is applicable to many safety issues in varying degrees. Like other analytical methods, its uncertainties can sometimes be so large as to make its insights of little use. In other cases, the insights are robust in spite of inherent uncertainties and can reveal technical facts, relationships, conclusions, and their uncertainties, so that the decision maker can better comprehend the issues.

Thus study is the first attempt within the waste-management community to systematically examine techniques for assigning probabilities to events and processes of concern in predicting the post-closure performance of geologic repositories. The study has been divided into two parts. The first part consists of a literature review that assembles and discusses existing techniques that can assign or can be helpful in assigning probabilities to events and processes of concern to long-term performance. This volume contains the result of the literature review. Much of the material may not seem directly applicable to repository performance assessment: the authors have found it necessary to draw on a wide variety of materials, some more clearly applicable than others. Each chapter concludes with a brief description of a technique that could be used immediately for assigning probabilities to the events or processes of concern. The techniques described in these sections are not necessarily the only ones currently available; neither are they necessarily the best that could be developed before licensing. Rather, these sections are intended to show whether at least one technique is available in each field that could produce probabilities acceptable under the EPA standard. The second part of the study will consist of selection and illustration of some of these existing techniques, or if necessary, development of new techniques, that could be used by the NRC in evaluating the license application submitted by DOE.

Goals

A brief review of scenarios developed for geologic repositories in bedded salt, domed salt, tuff, and basalt revealed moderate consistency in the events and processes considered capable of initiating releases from a closed repository. The events examined include faulting, seal failure, igneous intrusion, drilling, mining, subsidence, thermal effects, tectonics, dissolution, the effects of pumping, human intrusion, ground-water flow, thermomechanical effects, erosion, and glaciation. The primary goal of this study has been to search out and evaluate existing quantitative methods for determining probabilities of events and processes in selected fields that seemed to be closely related to some of these processes. Some of the events and processes of interest are geologic; others arise from the relation between human activity and geology. Finally, some events and processes are not geologic in themselves but affect some geologic event or process. Both rare events and continuous processes are considered. Techniques appropriate for the probabilistic treatment of rare events may differ from those that treat continuous processes.

Specifically, this study discusses existing quantitative methods for determining probabilities of events and processes in resource exploration, climatology, seismicity, tectonics, and seismic hazard, and volcanology. Secondary goals have included attempts to identify phenomena for which accurate probabilities cannot be estimated at this time and to identify areas of research that could improve significantly our ability to make estimates in the immediate future. These goals are a first step toward establishing a quantitative method for determining realistic probabilities of natural events and processes that will be objective, reproducible, accurate, and universally applicable. A second volume, to be published later, will attempt to choose between the various techniques described here and suggest which are most appropriate for use in performance assessments of geologic repositories.

Attempts are made here to treat only phenomena within the fields identified previously that are considered likely to contribute to performance of a geologic repository over a long interval (1,000 to 10,000 years). No assurance can be given that all significant factors have been examined here.

The uncertainty associated with the data used in generating each probability estimate must be specified. Uncertainties of various probability estimates of potential hazards must be propagated through the analysis of risk so that a realistic measure of uncertainty in total risk is obtained. Combining uncertainties may be accomplished by various means, including Monte Carlo, Maximus, and Bayesian techniques.

Methods of Determining Probabilities

"Probability" is considered to be synonymous with "likelihood" and "chance" in this report. Mathematically, the probability of a random event is the limiting value of relative frequency of occurrence reached in an infinitely long sequence of observations of that event. Even though individual outcomes of random events may not be predicted accurately, they will show statistical convergence to a given value over several occurrences or predictions of occurrence. In contrast, individual predictions of other types of events may be made with certainty because they do not behave as random events; these phenomena are called "deterministic." When initial values of various variables are adequately known, only one result will be realized for deterministic events, and this result can be predicted with complete certainty. Conversely, for random events, even though we know initial parameters adequately, we can predict future events or results only in probabilistic terms; that is, predict only in an ensemble sense, without the ability to predict individual outcomes. Methods for determining probabilities can be divided into axiomatic approaches, frequentist approaches, modeling approaches, and expert judgment. Which of these approaches is most suitable in a particular application depends on the complexity of the system producing the events whose probability is to be determined, how well the system is understood, and the number of data available.

Axiomatic approaches are theoretical in nature. The properties of a system are used to deduce possible outcomes of a trial and the probability of each outcome. Axiomatic approaches have been used to assign relative probabilities to some events and processes of interest to waste management. The axiomatic approach assumes that the system is well understood; few geological systems are simple enough or well enough understood to make an axiomatic approach practical.

Frequentist approaches depend on the analysis of existing data. Rather than determine what outcomes are possible in a system, frequentist approaches examine what outcomes have been recorded. The nature of the system need not be well understood if data are numerous enough to represent all possible outcomes. Unfortunately, "numerous enough" depends on the system; because the frequentist approach does not require any fundamental understanding of the system, an analyst can never know that one more trial will not produce a new outcome. Frequentist approaches have been used in waste management to assign probabilities to occurrences of such events as volcanism.

Modeling approaches entail developing a model of the system, allowing the system itself to be subjected to numerous trials by proxy. After gathering many data and preparing a computer simulation that incorporates all parameters known or suspected to play a part in determining an outcome, the modeler samples the input data in some way and executes numerous computer runs to determine probability. The modeling approach has been used in waste management in complex computer models such as GSM (Geologic Simulation Model).

The use of an axiomatic, frequentist, or modeling approach implicitly assumes that an event or process under consideration is random. Geologic events and processes for the most part are not random phenomena. They differ from truly random occurrences in two major ways. First, geologic phenomena rarely occur repeatedly under identical conditions. Therefore, geologic phenomena rarely, if ever, can constitute an infinitely long sequence from which theoretically correct probabilities could be determined. In addition, slightly different conditions introduced for each subsequent occurrence of an event or process will generate greater variances than normally would be encountered if randomness and identical conditions truly existed. Second, most scientists would agree that many geologic events and processes actually are deterministic phenomena and could be treated as such if we understood them adequately and had enough information to calculate these deterministic relationships. However, because of complexity in these phenomena and our lack of understanding of true relationships, we must treat many of them as probabilistic phenomena. This is completely satisfactory for scientific and regulatory purposes, but it does mean that we do not have as much accuracy and precision as we theoretically could have if they were handled deterministically. In the final performance assessments, however, some expert judgment and irreducible uncertainty will probably be present, necessitating a final decision from the NRC on the acceptability of the residual uncertainty and risk presented by the repository.

The use of expert opinion in assigning probabilities is more subjective and uncertain than the use of axiomatic, frequentist, or modeling approaches, but the EPA standard has explicitly given expert judgment an accepted place in performance assessment. In the absence of adequate data for probability determinations using axiomatic, frequentist, or modeling approaches, probabilities estimated by experts may be used for performance assessment. Expert opinion may be completely adequate to determine that probabilities are so low than an event is not of regulatory concern, for example. Expert opinion may also be useful when site-specific data are sparse and would be expensive or time-consuming to collect. Finally, great accuracy for a given probability may in many cases be unnecessary if consensus among experts about its possible range exists. Most commonly the basis for these estimates will be classical or empirical Bayesian methods. Bayesian probabilistic assessments may provide an evaluation of uncertainty associated with a probability estimate that is superior to that provided by objective probability determinations. This aspect commonly may be deficient in other probability determinations except for those derived from well established empirical distribution functions or cumulative distribution functions.

Estimating Probabilities of Geologic Events and Processes

Probabilities of natural events may be estimated in various ways. In general, the preferred order and basis by which probabilities of geologic events and processes should be estimated in performance assessments for potential geologic-repository sites is

Objective estimates obtained from
- Edf's derived from local data,
- Edf's derived from regional data,
- Edf's derived from global data,
- Pdf's or cdf's derived from theoretical basis,
- Limited observational data (too incomplete to establish edf or cdf);

Objective estimates (without distribution functions) established by
- Empirical Bayesian methods,
- Bayesian methods,
- Expert judgment;

Elimination of an event or process from further consideration by
- Consequence analysis,
- Bounding of probabilities;

Subjective estimates established by
- Delphi methods,
- Relative-probability estimation.

All of these methods are used in estimating probabilities of events and processes in the fields considered here (Figure E-1).

In determining probabilities of geologic events and processes for performance assessments, the question is not whether probabilities can be estimated or assigned to a specific event or process. Invariably probabilities can be and will be estimated, because the EPA standard requires this to be done. Rather, the correct question is "What is the most accurate means available by which realistic probabilities may be determined for an event or process at a specific site?"

As discussed above, probabilities may be estimated and assigned to natural events in various ways; some ways are more desirable than others. In general, objective, physically based probabilities are more satisfactory and more reliable than subjective, or judgmental, probabilities. A spectrum of quantitative measures exist, however. The following techniques for estimating probabilities of natural events and processes are discussed in order of generally decreasing preference.

Objective Probability Estimates from Empirical Distribution Functions. Four functions are of interest to the discussion of probabilities of natural events and processes. These are the empirical distribution function (edf), the cumulative distribution function (cdf), the probability density function (pdf), and the complementary cumulative distribution function (ccdf). An edf represents actual relative frequencies of sample data less than or equal to a given observation. Its graph is a step function whose steps are of height k/n, $1 \leq k \leq n$, and occur at each observation in a sample of size n. The graph therefore increases from zero to one. It shows the proportion of sample observations $\leq x$ for $-\infty < x < \infty$. A cdf represents the true probabilities of obtaining observations less than or equal to a given value. Because relative frequencies tend to approximate true probabilities as sample size increases, the edf approximates the cdf as the sample size increases. A pdf is the first derivative of a cdf, if the cdf is continuous. If the random variable is discrete, the pdf shows the probability of values of the random variable.

KEY

X Currently Feasible

? Possibly Feasible

	Resource Exploration	Climatology	Tectonics and Seismicity	Seismic Hazard	Volcanology
<u>Confidence Level</u>					
High			?		
Fair		X	X	X	X
Low	X				?
<u>Approach Taken</u>					
Axiomatic					
Frequentist	?	X	X		?
Modeling		X	X	X	
Expert judgment	X				X
<u>Source of Probabilities</u>					
Objective					
Edf (derived locally)			?		X
Edf (derived regionallly)	?		X		?
Edf (derived globally)	?		?		
Pdf or cdf (derived theoretically)					
Limited observational data (no edf or cdf)		X	X	X	X
Objective (without distribution functions)					
Empirical Bayesian	?				
Bayesian	?				
Expert judgment	?	X		X	X
Subjective					
Delphi methods		X			
Relative-probability estimates		X			

Figure E-1. Bases for probabilities assigned to events and processes in the fields considered in this report. Edf means empirical distribution function; cdf means cumulative distribution function; and pdf mean probability density function.

Roughly speaking, it is a density function that shows the likelihood of getting each value of x. The pdf at x of a continuous random variable X represents the relative rate at which the probability is accumulating in a neighborhood of x. A ccdf is equal to 1 - cdf and represents the probability that a random variable X > x. The EPA standard suggests that performance assessment contain complementary cumulative distribution functions.

Empirical Distribution Functions. Cdf's would provide exact probability determinations if they were available. Unfortunately, cdf's are rarely known in real applications: they must be estimated. The estimator for a cdf that is most free of assumptions is an edf derived from geologic data gathered locally. However, local data rarely will be adequate for this purpose and, hence, dependence will normally fall upon generic edf's derived from regional or, less satisfactorily, global data for the same geologic event or process. Generic data are less desirable than local data because geologic conditions rarely, if ever, will be identical for different geologic sites or times.

Natural variations in an event or process and observational errors always will be present to some degree in edf data. Whenever local, regional, or global edf's will be the basis for probability estimates, an investigator must decide whether a smoothing equation should be fitted to the edf (a cdf derived inductively) or whether an established family of cdf's (derived deductively) such as lognormal, gamma, negative beta, etc., should be fitted to the edf. Many mathematical and geological reasons can be found why a fitted cdf should or should not be substituted for an edf; rarely will the correct course be clear to an investigator. Fortunately, little damage and error will result probably in those cases where one course is not clearly better than another course. Substitution generally is not desirable if observational data fit two or more theoretical cdf's equally well; substitution is essential if one is concerned primarily with prediction of rare events that are represented poorly, or not at all, by available empirical data. Commonly, large or infrequent events are so poorly represented in the geologic record that substitution may be absolutely essential for accurate probabilities. In such a case, the analyst must pay special attention to the tails of the distribution, rather than using a distribution that fits the main central part of the data and extrapolating it to the tails without thought.

Fitting Curves to EDF Data. Many mathematical techniques have been developed for fitting curves to edf's; some methods are more appropriate than others under various mathematical or geological conditions, and some are totally incorrect under certain conditions. Therefore, care must be taken in deciding which method is to be used in any given case. Similarly, any technique used to determine a cdf or its associated pdf should be clearly described so that others may independently judge its validity for each specific situation.

Classical parametric methods of density estimation assume that certain mathematical conditions exist or are appropriate for data being fitted. These methods include maximum likelihood estimates, weighted least squares, and moments. Conversely, nonparametric techniques for density estimation have fewer mathematical assumptions regarding the form of the density function, but they require large sample sizes. These methods include, for example, maximum entropy and projection pursuit.

Theoretical Distribution Functions. Lacking an edf or a cdf derived from empirical data, the next best estimate of a pdf or cdf normally will be derived from theoretical considerations based on knowledge of the geologic event or process. For example, seismologists long ago expected theoretically that frequency of seismic events would follow a Poisson distribution because of the nature of these processes; observational data confirm that to a first-order approximation this is true. Historically, some distributions predicted theoretically have been reasonably close to subsequently observed data distributions; nonetheless, their accuracy directly depends upon our current understanding of a particular geologic event or process. In some instances, knowledge was poor at the time predictions were made, and theoretically derived cdf's have been significantly in error as a result.

Objective Probabilities without Distribution Functions. Often geologic data will be so incomplete that an accurate edf or cdf can not be determined from either available data or our existing knowledge of the event or process. Even so, some estimates of objective probabilities of future occurrences still may be obtained on the basis of expert judgment and extremely limited data. These probability estimates will be objective determinations made without benefit of an edf or cdf. An example commonly encountered in repository performance assessments is frequency of movement along a recent fault; total data obtained from field studies may consist of only two or three values. Uncertainty in these objective probability estimates typically will be great.

Elimination by Consequence Analysis or Bounding. In absence of any probability determinations by methods described above, an event or process of concern for performance assessments of repositories possibly may be eliminated from further consideration either through consequence analysis or by establishing bounds on the probability. When an event or process can be shown through either of these techniques to have potential results that are sufficiently insignificant so as to pose no danger to a repository, it may be dismissed from further consideration for purposes of performance assessments.

Subjective Probability Methods. Even for geologic events and processes that can neither be assigned probabilities through normal means nor be eliminated from further consideration by consequence analysis or bounding, additional techniques embodying great uncertainty remain. Subjective probabilities may be established using the expert judgment of several specialists from appropriate fields of geologic knowledge. Great uncertainties invariably are associated with subjective probabilities established in this manner because they represent, for example, a poor data base or one that can not be quantified easily. Each expert's opinion depends upon his own state of understanding of an event or process, experience, and abilities, and that similarity which he perceives as existing between the particular geologic situation of concern and other situations that are known and are comparable to varying degrees. In some instances, expert opinion has been shown to provide accurate evaluations, whereas in other instances it has been demonstrated to have been poor. Which will be the case for any given probability estimate obtained through expert opinion processes can rarely be assessed satisfactorily at the time probabilities are assigned.

Another technique is assignment of relative probabilities to events and processes based on general knowledge and individual or group understanding of them. These are subjective, order-of-magnitude estimates. Although relative probabilities will have the greatest uncertainties associated with them and they are the least desirable of all probability assessments, they may be sufficiently informative to be helpful in assessing performance risks. The basis for both probability and uncertainty estimates and the methods by which they were obtained must be stated clearly and explicitly so that others are able to freely evaluate the validity of each probability and uncertainty estimate.

Even such ill-defined probabilities as these generated subjectively may be adequate for some parts of the performance assessment, for example, where the estimated probability is very low or very high.

Resource Exploration

Human intrusion generally is considered to be one of the more likely occurrences that might compromise the integrity of a repository. These disruptions differ from other geologic processes and events in that the EPA and NRC offer specific regulatory guidance that may be applied in assigning their probabilities. The EPA does not think that developing a "correct" estimate of the probability of inadvertent human intrusion is possible, and therefore the Agency has limited the severity of the assumptions to be used in performance assessments. The NRC also limits the assumptions that can be made in predicting human intrusion for a performance assessment. The allowed assumptions bear directly on subjective probabilities that may be assigned in a performance assessment.

Resource exploration may be analyzed best by event trees that demonstrate the interdependent relationships between human activity and geologic factors as they affect estimates of probability of intersection of repository sites by boreholes and mining operations. No objective basis is known, however, for predicting future human activity or for realistically predicting future economic conditions that strongly influence exploration for mineral resources. Similarly, future normal drilling activity, independent of technological advances, economic conditions, and human activity, is impossible to predict for more than a few years.

Conditional probabilities that an exploitable resource is present in an area may be estimated easily if three values are known: (1) the probability that the specific resource (or specific aggregation of resources) occurs within the area of interest, (2) the commodity's or resource's relative demand, and (3) its exploitability/depth index. Relative demand determines whether there is incentive to search for a commodity, and the exploitability/depth index is a measure of the depth to which exploration will be carried out. Probability distribution functions must be derived from knowledge of the geology in the vicinity of a repository and data for analog occurrences of specific resources elsewhere. In general, data necessary for prediction of oil and gas resources are adequate; however, data for metallic and nonmetallic mineral resources are not adequate.

An alternative to objectively estimating probabilities for resource exploration is the "unit-regional value" (URV) approach, which estimates the value of resource wealth for some specified area based on past human activity and success in discovery of resources. This approach lumps all mineral commodities together according to their monetary value to measure the monetary value for the crust as a whole, treating it on a unit-area basis. This method contains serious limitations for predicting long-term exploration, including a limited data base spanning only 150 years of resource exploration; data from only limited portions of Earth; values that are averages for all resources combined; and local variations within a "unit" (regardless of size). In spite of its shortcomings, a URV procedure may be suitable for assessing the resource potential of proposed repository areas. Other statistical methods have been used to produce contour maps of the probability of occurrence of four specific groups of metallic deposits. Mapping has been carried out using geographic cells 2 km by 2 km in extent, each cell receiving values that express the probability that it has been correctly classified within each of the four groups. These probability values were contoured. The probability estimates pertain only to presence or absence of deposits and not to sizes or frequencies of deposits.

Numerous data bases exist for natural resources, but most available data reflect only quantities of production, economic value, and general exploration data for each specific resource. Few data have been compiled on sizes of specific deposits or occurrence of deposits known but not yet exploited. Statistical techniques for estimating success of borehole exploration and predicting specific areas of potential economic deposits have been developed for relatively simple geometrical situations, but have had little industrial application. A vast literature exists for oil and gas exploration, and some areas of expected future discoveries are generally known, although there is large uncertainty as to the statistical characteristics of populations of oil and gas fields that may be discovered. An adequate literature exists for metallic and nonmetallic resources, but areas of future exploration generally are known less well.

Major Conclusions

Objective estimates of probabilities for future resource exploration beyond more than a few years are not possible now; this probably will remain true indefinitely because resource estimates contain a large component dependent upon future human activity, economic factors, and technological factors that cannot be predicted realistically. Probability estimates for resource exploration will remain dominantly subjective, and uncertainty in these estimates will remain large. Subjective estimates can be influenced and supported by the use of URV or statistical approaches, however.

Objective resource-exploration analysis can be improved by determining more accurate areal shapes and sizes of specific resource deposits and by establishing a method for appraising when exploration in search of specific resources has exhausted an area. This new knowledge would permit more reliable subjective probabilities to be determined from objective geologic data in the vicinity of a potential repository site. In general, probabilities of future resource exploration resulting in breaching an established repository will be minimized if all conceivable resources in the area are present in no greater than average concentrations.

Climatology

No comprehensive effort has been made to predict climates of the next 10^3 to 10^6 years, although theory and techniques are now available that can be applied to the task. Predictive methods are being developed, but no study has so far combined all elements necessary to predict future conditions at the spatial resolution required for evaluation of repository sites. Interest in climatic variation resides in its ability to modify greatly environmental conditions; for risk assessment of geologic repositories specifically, this means changes in rainfall and its resulting changes in ground-water conditions and flow as well as potentially significantly greater loading of the surface by snow and ice.

Major components of the climatic system consist of Earth's atmosphere, hydrosphere, cryosphere, lithosphere, and biosphere. Each has different thermal characteristics and response times. The atmosphere responds relatively rapidly to changes in external controls, the mixed layer of the ocean more slowly, and the deep ocean and continental ice sheets extremely slowly. Each is related to other components through transfers of mass and energy. Interrelations are complex and may include feedback mechanisms that result in internal, "free" variations that are difficult to predict, as opposed to external, "forced" variations that are relatively easy to predict. Factors controlling climate may be external at one scale of climatic change and internal at another scale. External controls on time scales longer than 10^4 years include incoming solar radiation, atmospheric composition, and size and distribution of continents. On scales of 100 to 10^4 years, external controls include also ice sheets and temperature of ocean water and its circulation.

Climatic models can be classified into those that describe fast-response components of the climate system, such as the atmosphere, surface-energy and water balances, and mixed layer of the ocean, and those that describe slowly varying components, such as ice sheets and deep ocean. At time scales shorter than 10^4 years, slowly varying components may be properly regarded as external, "boundary-condition-like" factors. Models of rapidly varying parts of the climate system, chiefly atmospheric ones, can be divided into two groups. The first group explicitly represents the three-dimensional structure of the atmosphere, and in a sense, simulates day-to-day variations, i.e., weather. The second group simulates longer-term, spatially averaged weather, i.e., climate.

Individual climatic variables may be categorized into (a) those that describe <u>boundary conditions</u>, or external controls, of the climate system, (b) those that describe slowly varying components, and (c) those that describe fast-response components. Existing models of slowly varying components in climate that are necessary for long-term predictions are considered to be equilibrium models that cannot portray components as they change and evolve slowly in dynamic equilibrium with boundary conditions and slowly varying external controls. Consideration of components of the climate system, controls over their variations through time, and approaches taken in analyzing those variations suggests a potential strategy for developing climatic predictions over long time intervals. In particular, any prediction scheme for that time scale must necessarily have two parts. The first part consists of models of slowly varying components of the climate system that generate the temporal evolution of those components. The second part consists of models of fast-response components of the system that generate spatial details of a predicted climate that is in equilibrium with boundary conditions and slowly varying components. Development of a model containing a mechanism to handle slowly changing components that generate temporal evolution of those components in addition to fast-response components that generate spatial details that are in equilibrium with boundary conditions and slowly varying components is necessary. Although elements of the proposed model exist individually, their integration into a general climatic prediction model for future conditions has yet to be accomplished.

Problems also remain in knowledge concerning boundary conditions in the climatic system; dust loading and CO_2 concentrations of the atmosphere; variations in solar energy output; details of slowly varying components; and relative importance of forced and free variations in the system. Although fast-response components are understood much better than slow-response factors, knowledge remains limited. Spatial resolution and system details are poor, hydrospheric circulation and thermal characteristics are known inadequately, and better prediction of ice volumes spatially is required.

Three general data sets are needed in developing a climate-prediction scheme for the long time scale. The first set consists of past records of boundary conditions and slowly varying components of the climatic system, including the input of solar radiation to the climatic system, ice-sheet volume and extent, horizontal and vertical temperature structure of the oceans, CO_2 concentration, dust loading, and so on. The second set consists of comprehensive data on the spatial variability of the present climate to initialize models of fast-response components of the climatic system. Included in this data set are grid-point values of standard meteorological variables, as well as data such as sea surface temperature, land surface albedo, surface roughness, soil characteristics, and so on. To the extent that models of both slowly varying and fast-response components of the climate system have been developed, the basic data included in the first two sets could be said to already exist, although further development of the first data set may be required.

The third data set consists of data necessary for validation of model simulations. The scope of the data that could potentially be included in this set is large, including virtually any kind of paleoclimatic evidence. Although paleoclimatic data are numerous, they vary greatly in coverage both spatially and temporally, as well as in sensitivity to paleoclimatic variations. Comprehensive data sets are needed for specific times in the past. In addition, methods for comparing quantitatively paleoclimatic evidence with model simulations are needed.

Major Conclusions

The most appropriate measure of the relative performance of an overall climate prediction strategy would be its success in correctly predicting observed paleoclimates. In addition to facilitating the selection of individual models from the range of those available for the different components of a system, a model validation program would enable the value of the overall strategy to be assessed. A specific hierarchy of existing climatic models should be identified and evaluated as to its suitability for producing predictions that are required. Two specific aspects of the performance of an overall prediction strategy should be assessed; not surprisingly, these correspond to the slowly varying and fast-response components of the climatic system. The performance of any climate prediction strategy must be examined for its ability to correctly reconstruct both the temporal features of the paleoclimatic record (driven mainly by variations of the boundary conditions and slowly varying components) and the spatial features (determined largely by fast-response components). This evaluation should be used to guide further development of climatic predictions over long terms. A comprehensive program of model verification should be developed that includes required paleoclimatic data bases and methods for comparing model simulations with observed evidence. The scientific basis of climatic prediction on long time scales should be reviewed continuously in light of new understanding of climatic variation as it evolves and as new targets for prediction arise.

Prediction of changes by the model proposed will automatically provide probabilistic evaluations because of inherent variation in the system and uncertainty in parameter values used.

Tectonics and Seismicity

Determining the probability of tectonic activity and the probability of impaired repository performance as a result of such activity are to some extent separate activities, and this volume discusses them separately.

The geology of the repository site is the fundamental source of data for quantitatively evaluating tectonic and seismic hazards that could affect a nuclear-waste repository. In general, quantitative models at the whole-earth scale predict plate movements within millions of years, identify broad areas of Quaternary activity or potential activity, predict variations in plate positions and velocity that may cause major changes in intraplate strain, and identify areas of little orogenic or epeirogenic activity. Regional analyses evaluate broad patterns of faulting, tectonic sedimentation, epeirogenic movements, changes in fluvial and marine regimes, crustal stress environments, and so forth. The most quantitative and precise tectonic data available to predict future behavior at a given site come from local areas that have been active in Holocene or late Quaternary time ($<10^5$ years). Four kinds of geologic data are most useful for predicting potential tectonic activity near a waste repository: surface ruptures along fault zones; stratigraphic sequences related to tectonic activity; landforms related to surface rupture and regional uplift or subsidence; and relationships between seismicity and tectonic features.

Recurrence methods examine the presence and amounts of offsets of one or more dated units exposed naturally or artificially by a given fault trace. Most stratigraphic units either postdate or predate a given rupture event, and thus the ages of deposits that are and are not faulted by a given rupture bracket its age. Some deposits are inferred to have occurred during the rupture event itself. Some faulted stratigraphic units may be correlated with offset landforms like stream channels or terraces or with topographic fault scarps. Recurrence methods provide the best data set for probabilistic prediction of long-term behavior of a fault zone, but these methods often are severely limited by lack of proper age control. Stratigraphic sequences are probably the best single data source for fault recurrence studies, but only relatively young (late Pleistocene or younger) sequences offer significant resolution. Landform analysis, especially fault-scarp morphology, offers potentially significant information, but the precision is small, particularly from regional analysis. In every case, the best data are obtained when there has been late Pleistocene or Holocene tectonism and related sedimentation.

The use of recurrence methods requires some means of dating the deposits ruptured by a fault. Quantitative dating techniques include radiometric dating, paleomagnetic dating, tephrochronology, and dendrochronology. Relative age dating, which involves relative age assignment to suites of deposits, is the least reliable and least precise method of dating.

To the limited extent that earthquake prediction is possible, it depends on the availability of long- and short-term precursors, a well-established historical seismic record, and detailed monitoring networks for precursors of all kinds. Long- and short-term precursors of moderate to large seismic events have been extensively studied and quantified. Quantification generally is based on probabilistic models and standard statistical analyses. One critical view of earthquake prediction is that great earthquakes are not random occurrences, that the historic record generally provides an inadequate data base for proper statistical and probabilistic analysis, and thus that deterministic models may be more useful. A second view suggests that earthquake risk cannot be expressed in deterministic terms because of the enormous uncertainties about the nature and location of future earthquakes. The most significant problem with earthquake prediction is probably the lack of acceptable models that explain why precursors work. The greatest weakness of earthquake prediction is the lack of understanding of fundamental tectonic processes that create an earthquake source, particularly in intraplate settings. Predicting the maximum magnitude of an earthquake from the relationship between geologic features and seismicity associated with an earthquake source is a corollary problem to predicting earthquakes. In both seismic and aseismic areas, prediction of the magnitude of future events is largely based on the qualitative perception of the possible extent of rupture; few quantitative data exist.

A number of high-quality data bases are readily available for evaluating tectonic and seismic phenomena, although site-specific studies are few. Most tectonic data are in the form of geologic and tectonic maps, photoimages, cross-sections, isopach and structural contour maps, and fence diagrams. The major sources of data for seismic analysis are the World Wide Standardized Seismograph Network, National Geophysical Data Center, National Oceanic and Atmospheric Administration, US Coast and Geodetic Survey, UNESCO, and the National Academy of Sciences. Some data are raw seismic records on computer tapes; other data have been plotted and interpreted. Not all data are technically reviewed or formally published. Raw data are generally of high quality.

Perhaps the most significant uncertainty in tectonic analysis of waste repository sites is the determination of hazard in areas where little or no seismicity exists and where Quaternary--late Tertiary sedimentation and/or evidence for tectonism are minimal or non-existent. The eastern US is an example of this type of environment. There the main strategy for hazard analysis is quantifying regional stress; understanding the processes that cause this stress regime; and identifying and characterizing the tectonic features which may become hazards; that is, sources for significant earthquakes, preferential ground-water movement, and so forth. To a large extent, this approach entails evaluating inactive basement features with the potential to be reactivated. Earthquake hazard analysis in aseismic or weakly seismic regions requires that the process of reactivation of basement structures be understood. If the stress regime acting on a known tectonic feature with predictable failure mechanisms is known, then it may be possible to predict the magnitude and location of the seismic hazard. This approach has yet to be quantitatively tested.

A second, more theoretical step in this analysis is evaluating the tectonic processes that may be acting on the region to yield the observed regional stress-strain patterns. A number of important regional tectonic processes have been suggested. The first is the stress regime created by the plate-tectonic process. Most modern authors consider trench-pull and associated traction on the subducted slab to be the critical force that generates stress in the plates. Additional significant stresses are created by thermal perturbations, ridge-push, variations in crustal and lithospheric thickness, membrane stresses from variations in earth curvature, and erosion and sedimentation.

In addition to plate stresses, the regional picture is complicated by more local phenomena such as stress corrosion and chemical effects within the lithosphere; localized movement along zones of different mechanical properties; large- and small-scale lithospheric compositional or rheological inhomogeneities; stress amplification; enhanced fluid pore pressure and associated hydrolytic weakening of minerals such as quartz in the upper lithosphere; stress-induced crack growth in stressed regions; and brittle reactivation of previously ductile zones due to later uplift. Methods that establish the causes and present state of crustal stress and that characterize the tectonic features of a region offer significant potential for creating more realistic performance assessments. This method can generate a factual matrix of relevant physical characteristics and a statistically quantitative estimate of tectonic/seismic hazard using expert opinions of a broad range of earth-science professionals.

Major Conclusions

A number of studies have attempted to outline procedures for performance assessment in tectonics and seismology. The major problems associated with such assessments are inadequate data collection; disagreement between professionals about the quality and significance of the data; significant uncertainty in the level of current scientific understanding and in the available data; and the inability to assign meaningful and generally accepted probabilities. At present, no tectonic or seismologic method is completely adequate to quantitatively assess, with a high degree of certainty, the probability of tectonic activity at a repository site.

Seismic Hazard Assessment

Probabilistic analysis of the threat of seismological effects at a site integrates two basic elements. The first is a general earthquake recurrence model: a probabilistic prediction of future earthquake dates, locations, and source characteristics. The second element is a probabilistic prediction of the effects at the site given the location and source characteristics of an event. The site effects of interest may include one or more measures of strong ground motion and/or faulting. Assessment and analysis of the uncertainties in such probabilistic hazard studies has become routine in practice.

The standard assumption in most probabilistic analyses of seismic shaking is that earthquakes occur as a Poisson process. A key property of the Poisson process is lack of memory; the probability distribution of the time to the next earthquake is independent of the time since the previous earthquake. In addition to the Poisson assumption, the assumption is routinely made that the magnitude and location of the next event are independent of the time since the previous earthquake, its magnitude, and its location. Finally, it is generally assumed that magnitudes follow a doubly-truncated exponential distribution and that locations follow a piecewise-uniform distribution; each region of uniformity is called a seismic source and is usually associated with a geologic or tectonic feature or an area of high historic seismicity. Poisson models are simple and have the highest possible degree of probabilistic independence. The parameters of this model are the expected number of earthquakes per year for each magnitude class and each seismic source.

A number of magnitude-recurrence models that contain more memory than the Poisson model have been proposed. Some of these models try to incorporate certain dependencies suggested by a physical understanding of tectonic processes. Renewal-process models differ from the Poisson model in that the distribution of inter-arrival times is not necessarily exponential. Dependence between inter-arrival time and magnitude is introduced in the so-called time-predictable and slip-predictable models. In time-predictable models, the distribution of the time to the next earthquake is dependent on the size of the previous earthquake: the larger the previous earthquake, the longer the wait to the next earthquake. In slip-predictable models, the distribution of earthquake magnitude depends on the time since the previous earthquake. A general semi-Markov model can also include all these possible dependencies. A "characteristic-process" model, in which a feature produces two kinds of earthquakes, has also been postulated. Large (characteristic) earthquakes follow a renewal-process model, and smaller (background) earthquakes follow a Poisson-exponential model.

Some models attempt to predict the temporal and spatial dependence of seismicity. An example of this dependence is the highly enhanced likelihood of earthquakes occurring on seismic gaps. Hybrid stochastic-mechanical models of earthquake occurrences in space and time and a Markov model in space and time have been proposed. Physical models that include stress accumulation, rupture initiation, and (static or dynamic) rupture propagation have been investigated. Combined with a stochastic-process description of strength along the fault, these models have a potential for engineering applications.

Earthquake-induced shaking may affect the performance of repositories during the period of waste loading and after closure. The mechanisms of damage during the loading period would be similar to those experienced in a deep mining operation: damage to above-ground facilities, damage to the vertical conveyance system, rock spalling, and collapse of tunnels. All these mechanisms may potentially lead to releases of radioactivity from waste temporarily stored above ground, in transit, or in permanent storage. These damage mechanisms may compromise the integrity of one or more of the following containment barriers: the rock mass in the vicinity of the opening; the tunnel liner; the closure system (backfill and plugs); or the waste package. Mechanical damage to the waste package would likely be caused by unsatisfactory performance of the backfill or the rock mass, not by the shaking itself.

The amplitude, frequency content, and duration of shaking at a site on the surface is the combined effect of three factors: seismic source characteristics, propagation of seismic waves in the crust, and local effects due to soil and subsoil conditions. Most measurements of shaking are made at sites on the surface. Earthquake ground shaking in deep tunnels is different from that on the surface even at rock sites because amplification caused by a free surface and filtering of high-frequency waves by weathered bedrock beneath the site are absent.

Stochastic methods use a probabilistic representation of the energy radiated by the seismic source or of the slip on the fault. They use simple concepts of wave-propagation theory to model the effect of propagation path and free-surface amplification. Stochastic methods may be divided into two broad categories: those that start from a more abstract representation of the seismic source and those that model the kinematics or dynamics of slip on the fault. Most methods in the first category use a source spectral representation, which relates the amplitude and shape of the Fourier spectrum of acceleration to two parameters: seismic moment (a measure of earthquake size) and stress drop on the fault. (Some authors prefer to consider stress drop an empirical, rather than physical, parameter.) For given seismic moment, stress drop, and distance, these methods yield the power spectral density and duration of ground acceleration. Peak accelerations, velocities, spectral displacements, and other measures of ground motion are then calculated using random-vibration theory. In essence, these methods are not too different from semi-empirical scaling methods; they differ only in their assumptions about source scaling and in their mathematical rigor. Stochastic methods satisfactorily predict ground motion in California.

Deterministic methods generate synthetic "seismograms" from a (usually kinematic) representation of slip at the source and detailed modeling of wave propagation through detailed models of the crust. Most of these methods use non-uniform spatial distributions of slip; usually, the distribution of slip is modified until agreement is obtained with the observed suite of seismograms being modelled. In order to properly model the frequencies of engineering interest, observed records from smaller events are summed to yield the ground motion from a larger earthquake.

Major Conclusions

Two classes of models are available for evaluating probabilities of faulting. In a magnitude-occurrence model of faulting, the same models used to estimate probabilities of ground shaking can be modified to predict probabilities of faulting at the site. As in models for the probabilistic characterization of shaking, earthquake occurrences are characterized as a marked point process in space and time; magnitude is used to characterize earthquake size. Instead of an attenuation function, an influence function characterizes the extent of faulting. The influence function takes values of zero (no faulting) or one (faulting), may be defined in three dimensions (i.e., it includes rupture depth), and may be anisotropic (i.e., the rupture is likely to follow some preferred directions of faulting). The extent of the influence function depends on magnitude, but it has a random component. Faulting-occurrence models directly attempt to characterize the occurrence of faulting as a random process in space and time without using earthquake magnitude as an intermediate variable.

Volcanology

Volcanic processes commonly are considered on three scales: continental, regional, and local. Validity of probabilistic estimates of volcanic eruptions generally improves as scale diminishes because the data necessary for prediction improve. The potential for igneous events in broad tectonic regimes is governed by global plate motion and large-scale crust-mantle relations. On this scale, methods of calculating probabilities depend almost entirely on interpretations of theoretical concepts, many of which are difficult to test by rigorous standards. The validity of these concepts must be evaluated from a fragmentary geologic record, and in many instances, this involves judgements with a large element of subjectivity. Data are drawn from geophysical observations on a continental scale and from a geologic record extending back millions of years.

The potential for igneous events on a regional scale must be assessed in terms of prior activity and the thermal and stress regimes in specific regions. Investigations to assess probabilities at this scale focus on a region within the effective radius of any igneous event that would have an impact on the specific site under investigation, but the geographic limits of the area to be examined will differ according to the type of activity being considered. Most studies have concluded that the most serious possible event on this scale would be a large-scale fissure eruption capable of blanketing thousands of square kilometers with flood lavas or pyroclastic flows.

Because the repository sites being investigated by DOE are not close to volcanic centers with a record of historic activity, techniques for determining the potential for igneous activity within the immediate vicinity of a volcano are of limited usefulness to the question of nuclear-waste disposal and need not be considered here. Although some of the methods of calculating probabilities could be of general use, the methods have limited application to regions of very infrequent activity and few historic data. Nevertheless, the efficiency of monitoring techniques in forecasting eruptions may be an important factor in estimating probabilities, because they will determine the lead time that may be available before an igneous event could disrupt a repository. These techniques could be applied to a variety of types of regions, including those with no record of previous activity, and could be important tools in the future.

Probability estimates of future events are derived from knowledge of past activity. Thus predictions in areas of recent activity will be good to excellent generally, whereas predictions may be extremely poor in stable portions of Earth's crust that have not undergone recent activity and that are unlikely to have volcanic activity for many millions of years in the future. In these latter cases, some forewarning of activity is likely to be obtained from geophysical data; however, without experience in detecting these types of events, we have no objective basis for knowing what lengths of time might be involved with these warnings.

To determine probabilities of future events, the stratigraphic record must be searched in the vicinity of interest, and to a limited extent in regional records, for all evidence of past volcanic activity. Each event must be dated radiometrically, paleomagnetically, or stratigraphically to determine the frequency of eruption. In addition to frequency, magnitudes and extent of area affected by each eruption may be determined and probabilities assigned to each aspect.

Eruptions tend to be either explosive, sending debris over a large area, or quiet, sending lava over a restricted area. Explosive eruptions are far more dangerous than quiet eruptions. Quiet eruptions normally will have an excellent record locally, whereas evidence of explosive events is more likely to be lost in the stratigraphic record, even though widespread, because the deposits will be thinner and much less resistant to weathering and erosion. Missing just one past explosive event in the stratigraphic record could significantly alter a probability estimate of future activity and hazard assessment.

Probability estimates of volcanic activity normally assume that volcanism will continue in the future at the same rate it has proceeded in the past. Regional studies recently have indicated that this assumption may not be valid for certain regions. Thus studies of a region's overall volcanic behavior should be made for each potential repository to determine whether evidence for the geologic province suggests either increasing or decreasing rates of activity.

Major Conclusions

Although methods for estimating probabilities of volcanic activity are well established and data are readily available, large uncertainties normally will be associated with the probabilities. Uncertainty is large because the basis of estimation commonly consists of a limited number of events because of past frequency and areal extent of eruptions. A statistically good sample population does not exist, and good empirical distribution functions cannot be established for probability estimates. In addition, volcanism tends to be episodic on all three scales. The "eruption rate" obtained from these data will differ dramatically depending on the time interval used and the way in which events are distributed within that interval. Because volcanism is so episodic, both locally and globally, this problem will be encountered in almost every province and on every scale of measure. Unless one can define the temporal pattern of events and can say where we are in a cycle at a given time, the probabilistic calculations have little meaning. Evidence normally is insufficient at the local scale to determine where a site is on the temporal cycle of activity. Episodicity is less likely to be a problem as quantity of data increases because apparently a linear relationship exists between duration of quiescent intervals and the logarithm of the number of quiescent intervals.

The newly developing field of seismic tomography offers good potential for a much improved method for prediction of volcanic activity in both volcanically active and inactive portions of Earth's crust. This method identifies and maps varying physical properties of materials in Earth's interior, such as thermal anomalies and the presence of bodies of magma. Thus this technology should be capable of predicting more accurately localities of potential volcanic activity long before surface eruptions occur than presently is possible.

Chapter 1

INTRODUCTION

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Abstract

The US Environmental Protection Agency has recently published a probabilistic standard for releases of high-level radioactive waste from a mined geologic repository. The standard sets limits for contaminant releases with more than one chance in 10 of occurring within 10,000 years, and less strict limits for releases of smaller probability. The standard offers no methods for determining probabilities of events and processes of interest, and in the past no consensus has existed in the waste-management community on how to do this. Sandia National Laboratories is developing a general method for determining probabilities of a given set of events and processes; this volume reviews the existing literature on techniques for the probabilistic prediction of the occurrence of various phenomena that might affect a geologic repository. Many events and processes that will be considered in a performance assessment can be treated deterministically or probabilistically using a systematic and repeatable method such as that outlined tentatively here. It would be useful to the waste-management community to reach some agreement on the steps to be included in establishing probabilities for risk assessment methods.

General Discussion

The US Environmental Protection Agency (EPA) has recently published environmental standards for the management and disposal of spent fuel (SF) and high-level and transuranic radioactive waste (HLW and TRU) (EPA, 1985). The standard governs the allowable releases from potential geologic repositories for the disposal of commercially generated nuclear waste. The standard is probabilistic. It sets certain limits for contaminant releases that are estimated to have more than one chance in 10 of occurring within 10,000 years, and a less strict set of limits for releases estimated to have between one chance in 10 and one chance in 1000 of occurring within 10,000 years. No limits are set for releases of lesser probability. The standard requires performance assessments that estimate probabilities of events and processes that might cause or permit releases of radioactive waste from repositories, but it does not offer any guidelines for methods of determining probabilities. The US Department of Energy (DOE) is responsible for preparing performance assessments as a part of a license application for a waste repository. The US Nuclear Regulatory Commission (NRC) must determine whether each performance assessment is adequate during licensing proceedings. The Waste Management Systems Division of Sandia National Laboratories in Albuquerque, under the sponsorship of the NRC Office of Nuclear Material Safeguards and Safety, is leading an effort to develop a method that can be used to determine probabilities for a given set of geologic events and processes considered to be potentially hazardous.

No consensus has existed in the past in either the waste-management or geological communities as to how probabilities of geologic events and processes should be determined. Methods used by waste-management scientists have differed widely. In some cases, events and processes have been chosen for preliminary performance assessments without any published consideration of probabilities (Arnett and others, 1980). Some workers have assumed probabilities (Pepping and others, 1983). Some probabilities have been calculated with fairly sophisticated mathematical techniques, but using limited or uncertain data (Claiborne and Gera, 1974; Crowe and Carr, 1980; Cranwell, Campbell, and others, 1982). Other studies have used a combination of these methods, depending on the availability of data (Hunter and others, 1983). The general geological literature also contains examples of probabilistic analysis of geologic events and processes that are based on a variety of techniques (Simpson, 1952; Rantz, 1964; Gretner, 1967; Clifton, 1978; Sadler, 1981; Carr, 1982). These methods have ranged literally from informed but unsupported guesses to elaborate calculations that may represent the best approximations that can be made today with available data. Methods commonly have contained a significant subjective component--representing an individual's experience, judgment, or assumptions--which may or may not be explicitly stated. Few applications have involved adequate data bases, and therefore their results must remain suspect.

This study is the first attempt within the waste-management community to systematically examine techniques for assigning probabilities to selected events and processes of concern in predicting the post-closure performance of geologic repositories. Because so many events and processes are of concern to the 10,000-year performance, and because so much work has been done that either directly or inderectly applies to the problem, the study has been divided into two parts.

The first part consists of a literature review that assembles and discusses existing techniques that can assign or can be helpful in assigning probabilities to selected events and processes of concern to long-term performance. This volume, Volume 1, contains the result of the literature review. Much of the material may not seem directly applicable, at first glance, to repository performance assessment. Because this volume is the first in what might be called a new field of study--probability assignment for performance assessment--the authors have found it necessary to draw on a wide variety of materials, some more clearly applicable than others. Each chapter concludes with a brief description of a technique that could be used immediately for assigning probabilities to the events or processes of concern. The techniques described in these sections are not necessarily the only ones currently available; neither are they necessarily the best that could be developed before licensing. Rather, these sections are intended to show whether at least one technique is available in each field that could produce probabilities acceptable under the EPA standard.

The second part of the study will consist of selection and illustration of some of these existing techniques, or if necessary, development of new techniques, that could be used by the NRC in evaluating the license application submitted by DOE. This volume is thus the first step toward the ultimate goal of establishing a quantitative methodology for determining probabilities of events and processes that is objective, reproducible, accurate, and universally applicable. Such a quantitative methodology presumably would generate the consensus that will be desirable during licensing proceedings.

Some of the events and processes of interest in performance assessment are geologic, e.g., fault movement. Others arise from the relation between human activity and geology, e.g., exploration for resources. Finally, some events and processes are not geologic, but affect some geologic event or process, e.g., climatic change that alters ground-water flow. Some of the phenomena considered here are sudden events that may be rare, such as a volcanic eruption. Others are continuous processes that are certain to occur, such as climatic change. Techniques appropriate for the probabilistic treatment of rare events may differ from those that treat continuous processes.

Using Probabilities in Performance Assessment

A brief review of scenarios developed for geologic repositories in bedded salt (Bingham and Barr, 1979; Cranwell and others, 1982), domed salt (Harwell and others, 1982), tuff (Hunter and others, 1983), and basalt (Hunter, 1983) revealed moderate consistency in the events and processes considered capable of initiating releases from a closed repository. Bingham and Barr (1979) considered faulting, seal failure, igneous intrusion, drilling, mining, subsidence, thermal effects, and tectonics to be important, along with a few events specific to the WIPP site. Cranwell and others (1982) considered drilling, seal failure, and dissolution to be important release phenomena and the effects of pumping, faulting, and igneous intrusion to be important transport phenomena. Harwell and others (1982) examined the effects of a large number of geologic and human processes and events and concluded that only human intrusion was important enough to analyze. Hunter and others (1983) considered the effects of ground-water flow, tectonics, thermo-mechanical effects, igneous intrusion, subsidence, drilling, faulting, seal failure, and erosion. Hunter (1983) examined the effects of ground-water flow, tectonics, faulting, glaciation, erosion, thermomechanical effects, subsidence, seal failure, and drilling.

This report examines whether techniques are available to assign probabilities to initiating events and processes (hereafter called simply "events"); in contrast, the probabilities of concern in performance assessments are those of individual releases, i.e., of scenarios. The scenarios arising from the initiating events (e.g., Figure 1-1) include many subsidiary events whose occurrence may or may not depend on the occurrence of the initiating events. To determine the probability of each scenario, we must know not only the probability of the initiating event, but the conditional probability of each subsidiary event. A systematic examination of what these subsidiary events might be (i.e., scenario development) or of what the probabilities of any of the initiating or subsidiary events might be (i.e., probability assignment) is beyond the scope of this volume. For the most part, only techniques for assigning probabilities to initiating events are discussed here, for three primary reasons. First, probability assignment for performance assessment is in its infancy, and this literature review represents only an initial effort to find and evaluate, not to apply, the appropriate techniques. Second, site-specific data are necessary for developing scenarios or assigning probabilities, and no site has been chosen. Finally, a suite of scenarios must be developed before the subsidiary events of importance are known.

For example, Chapter 3 discusses techniques for predicting climate. Changes in climate will not directly affect a repository at a depth of a few thousand feet: of interest is the probability that, say, ground-water recharge and flow will change as a result of climatic change. Chapters 4 and 5 describe techniques for the probabilistic prediction of tectonic or seismic events and the hazards that result from these events. Only when such events lead to changes in the rock or repository that detrimentally affect waste containment are they of interest to performance assessment. Resource exploration (Ch. 2) and volcanism (Ch. 6) could release waste directly from the repository to the accessible environment, and thus their probabilities might be more directly used in a performance assessment. Even releases following these events, however, commonly involve many subsidiary events whose probabilities must also be determined.

Goals of this Study

The primary goal of this study has been to search out and evaluate existing quantitative methods for determining probabilities of events and processes in selected fields that seemed to be closely related to some of the initiating events considered important to long-term performance by the earlier workers mentioned above. These fields are resource exploration, climatology, seismicity, tectonics, and seismic hazard assessment, and volcanology. All

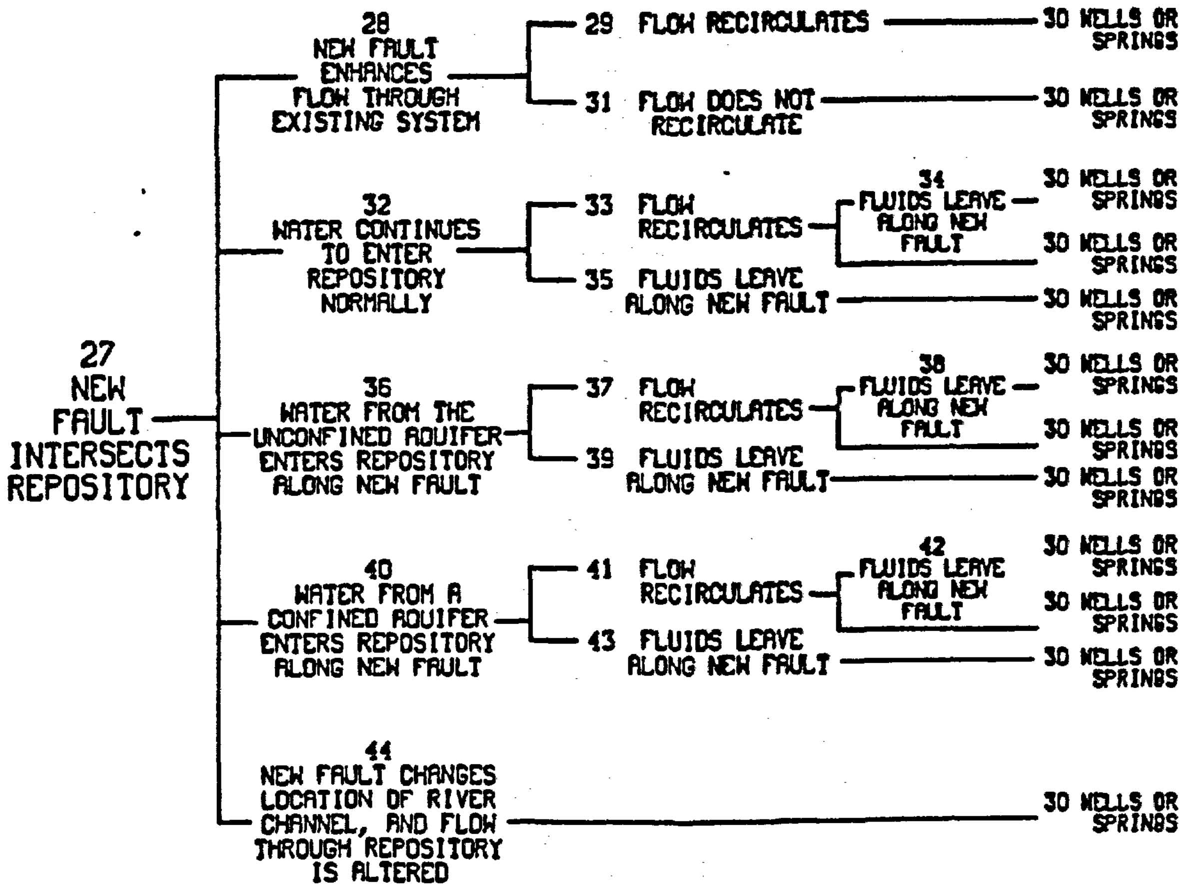


Figure 1-1. Example of an event tree containing several scenarios (Hunter, 1983).

were chosen because they encompass geologic events and processes that can initiate releases of radioactive waste from a geologic repository. The quantitative methods for determining probabilities identified here are those that have been reported in the literature, and some that could be used but have not been reported. Merits and limitations of each method have been described, and the current availability of data bases adequate for determining accurate probabilities of events and processes has been appraised. A secondary goal has been to identify phenomena for which accurate probabilities can not be determined now and areas of research that could materially improve our ability to make better probabilistic predictions in the immediate future. Knowing what methods exist, what their merits and limitations are, and what methods remain to be developed will enable the NRC to accurately judge the reliability of any probabilities contained in licence applications submitted by the DOE.

Attempts have been made here to treat only phenomena within the fields identified previously that are considered likely to contribute to performance of a geologic repository over a long interval (1000 to 10,000 years). No assurance can be given at this time that all significant factors have been examined in this report. Similarly, not all fields of geology or associated sciences known to bear upon long-term performance of a geological repository have been considered here; nor have possible interactions between fields and their importance to long-term performance been considered or evaluated here. Comprehensive consideration of all possible contributors to performance of a geologic repository will be necessary in later stages of development of a probabilistic methodology for performance assessments of potential geologic repository sites.

No attempt has been made in this volume to determine probabilities for specific events or processes at given sites or to assemble the data necessary for such an exercise. Determining probabilities for use in performance assessment requires, at minimum, a good, site-specific data base and a fairly comprehensive suite of site-specific scenarios. Furthermore, it is not the function of the NRC and its contractors to carry out all the steps of performance assessment for geologic repositories, but rather to evaluate performance assessments prepared by the DOE. Thus, the second volume will illustrate selected methods in order to show that practical methods exist and to enable the NRC to judge whether appropriate methods have been used by the DOE in license applications. NRC may or may not choose to use the methods and data bases described here by itself assigning probabilities to site-specific events and processes during licensing proceedings. Neither has this study attempted to include a comprehensive discussion of uncertainty analysis or of the uncertainties that may be present in data, conceptual models, or numerical models and codes.

Regulatory Background

Role of Probabilistic Calculations in the Regulatory Process

Calculations of probabilities of rare events and processes can and will play an important role in regulatory decision-making. This is true in part because EPA and NRC regulations require that certain probabilistic calculations be performed to support regulatory decisions; but an important additional reason is that these types of calculations provide insights that cannot be obtained in any other way.

The formal use of probabilities in evaluating phenomena is embedded within the EPA standard on high-level radioactive waste management (EPA, 1985). The EPA standard requires that the likelihoods of occurrence of events and processes be calculated. The standard treats different types of events differently, permitting elevated releases for some events if their probability is estimated to be sufficiently small, and permitting some event types of even smaller probability to be dropped entirely from detailed consideration. NRC regulations (NRC, 1983) have been framed to provide reasonable assurance that the EPA standard is met.

Over and above this formal use of probabilities, the role of probabilistic calculations is sure to be significant in providing a broad perspective on overall repository performance. Because the NRC staff has had a decade of experience with using probabilistic methods to support reactor-safety decision-making, their use in the high-level radioactive waste regulatory arena is sure to be extensive--more extensive than if this decade of experience had not existed. The NRC has had an opportunity to consider just what role these methods can play, what their limitations are, and why. Probabilistic methods have their largest impact in reactor-safety regulation in

- quantitatively calculating core-melt frequency and offsite risk,
- providing a perspective on linkages among various aspects of overall safety design,
- establishing the relative importance of various issues,
- prioritizing inspection and quality-assurance activities,
- assisting in development of regulatory guides, branch technical positions, and similar subsidiary regulatory positions, and
- prioritizing research projects.

The use of probabilistic methods in formal reactor-safety regulations and regulatory guides is less extensive, mainly because both regulators and licensees must work from a more structured, deterministic regulatory approach. This thought is expressed well in a recent NRC report on the role of probabilistic methods in reactor safety regulation (NRC, 1984):

> In recent years, it has been recognized that PRA ["probabilistic risk assessment," the name given to probabilistic analysis of the safety of reactors] can offer the regulator a realistic description, probabilistic in character when necessary, that is applicable to many safety issues in varying degrees. The integral nature of the analysis and the explicit consideration of the interactions between systems can shed additional light on an issue. PRA is, of course,

only one of many regulatory tools, and its applicability is not universal: for some issues it cannot shed much light at all. Like other analytical methods, its uncertainties can sometimes be so large as to make its insights of little use. In other cases, the PRA insights are robust in spite of the inherent uncertainties. At times, the ability of PRA to focus attention on the uncertainties resulting from a lack of knowledge provides vital information to the regulator, even if the level of risk is not well defined. Like any analytical method, PRA cannot, and should not, dictate a decision. It can only lay out technical facts, relationships, conclusions, and their uncertainties, so that the decisionmaker can better comprehend the issues.

PRA offers a quantitative analytical technique for integrating diverse aspects of geological events, processes, and other phenomena and their effects upon a potential geologic repository in order to evaluate realistically what hazards they may hold for safe storage of nuclear waste. PRA is a bottom-up approach that calculates overall performance from the performance of individual details of a system. It also identifies what informational bases are required for accurately analyzing generic and site-specific aspects of potential geologic repositories. In addition, it can provide helpful insights into geologic processes.

Just as probabilities of natural events and processes must be realistic for accurate PRA, uncertainties, or error bands, assigned to probabilities must be realistic, because of the ambitious goal of PRA, namely overall consequence calculations. In addition, uncertainty measures must be propagated realistically throughout calculations for PRA even though vastly different mathematical techniques may have been used in determining various probabilities. Therefore, probabilistic modeling necessarily must carefully consider variation in natural phenomena, measurements errors in input data, uncertainties in modeling, and uncertainties in techniques employed in assigning probabilities to geologic events and processes.

In Appendix B of its standard, the EPA explicitly assumes that a number of techniques will be appropriate for predicting the likelihood of events and processes that may disturb a repository. Complex computational models, analytical theories, and prevalent expert judgment are assumed to be appropriate techniques. In addition, the EPA assumes that, because of the uncertainties likely to be present, the NRC may choose to supplement the predictions with qualitative judgments.

Project Approach

An ideal method would model probability determinations in a completely general fashion for all possible geologic conditions. In practice, this study must emphasize events and processes that are thought to be likely and of greatest concern at sites the DOE is currently considering. Furthermore, a preliminary study such as this necessarily concentrates on these events and processes that have been treated in the existing literature.

Experts in the fields mentioned above were assembled. Each worked independently to assess quantitative methods for determining probabilities of events and processes that have been reported in scientific literature in his field of expertise. Each attempted to identify other methods that could be used and existing data bases with which probabilities can be calculated. Their work is presented in Chapters 2 through 6 of this report. The individual studies have been combined with an Executive Summary and Introduction to form this report. During the course of this work, the experts met twice to plan and discuss the work and solve problems as a group. Each expert has included a description of a currently feasible approach to probability assignment in his chapter; these descriptions do not necessarily reflect the opinions of the other authors or of the Waste Management Systems Division.

One premise of this study was that most geologic events and processes can be sorted into one of three groups when attempting to assign probabilities of future occurrence. These groups are those for which probabilities can be determined with high confidence, fairly accurately, or only with limited confidence (i.e., containing inherently large uncertainty) (Hunter and others, 1985).

The timing and nature of some events or processes can be predicted with high confidence, because the area of concern is well understood and because quantitative development of the subject is well established on either theoretical or empirical grounds. These events and processes are in the first group. Many natural events or processes are deterministic or virtually so. For example, heat production and changes in inventory in a radioactive source can be predicted with great accuracy, given data on the initial inventory. This process can be treated deterministically with great confidence. The physics of fluid flow through porous media is well established theoretically (Davis and DeWiest, 1966; DeWiest, 1969; Marle, 1981); numerous quantitative models have been developed and applied to real geologic situations to predict ground-water movement; and hydrologists generally agree that several established methods and techniques provide acceptably similar results (Davis and DeWiest, 1966). Thus ground-water flow within some aquifers and basins also can be predicted, although the accuracy of the prediction depends on data that may not be readily obtained. Generally speaking, hydrologic data from sites currently being considered by the DOE are sparse. Inadequacies in the data make uncertainty and sensitivity analysis of the predicted flow necessary. If a DOE site is in a basin in which porous flow dominates, then ground-water flow could be well understood after appropriate data are collected and ground-water flow is modeled.

Phenomena in the second group can be treated probabilistically with reasonable accuracy today. Adequate data bases exist, or may be easily obtained, to estimate their probabilities by establishing empirical frequency distributions and thereby estimating their probability density functions. This may be done even though we do not fully understand the mechanism driving the event or process. Phenomena might also fall into this group because data are inadequate to use existing deterministic models, because the process is too poorly understood to create deterministic models, or because the process can be considered random. An example of this might be volcanic eruptions in western United States (Crowe and Carr, 1980). Thus phenomena that would normally be included in the first category when adequate data are available might be relegated to this second category in the absence of adequate data. Some phenomena can be predicted based on general geologic knowledge to be nearly certain to occur in a given area during a long enough period of time. For example, Quaternary volcanism is entirely restricted to the western United States, where an upper lithospheric plate is above a subducting plate margin. Here active volcanoes exist today (Williams and McBirney, 1979). Their frequencies of eruption during Quaternary time are generally well known (NOAA Data Center) from geologic data. Some sites being considered, such as the basalt, tuff, and Paradox Basin sites, are well inside this area of Quaternary volcanism. Because young volcanoes tend to be easily identified in the arid West, existing data are usually adequate. Even though it is not possible to predict deterministically when or where a volcano will erupt next, the process is well enough understood that it can be stated that some will occur in the West. Moreover, enough data exist to determine the past rate of new eruptions in the West, and therefore (assuming that the rate continues unchanged), the probability of new eruptions. In fact, just such a calculation has been made for the tuff site in southern Nevada (Crowe and Carr, 1980); the probability of new eruptive vents was estimated from the known number of volcanoes and their frequency of eruption. Because the Gulf Coast salt domes being considered for nuclear waste disposal are well outside the area of Quaternary volcanism, volcanism probably need not be considered in salt dome performance assessments.

Extreme values of some geologic parameters may be difficult to predict with great accuracy even when the parameters are well understood and available data are excellent. For example, whether future seismic events will exceed some stated level of energy release is uncertain. Seismologists have used Gumbel's theory of extreme values (Shakal and Willis, 1972), Markovian models (Patwardhan and others, 1980), and maximum entropy (Berrill and Davis, 1980), as well as assuming various probability distributions to estimate maxima that may be expected for future extreme values. Many such extreme values may have very small probabilities, however, and Appendix B of the final EPA standard (EPA, 1985) suggests that performance assessments need not consider events and processes that are estimated to have less than one chance in 10,000 of occurring over 10,000 years. For events of very small probability, a rough estimate of probability may be adequate to demonstrate compliance with the standard.

Phenomena that fall into the third and final category, however, present major difficulty because they can be predicted only poorly and with limited confidence. The mechanisms driving the event or process may be inadequately understood, or data may be inadequate to make accurate predictions. Geologic events and processes that are included in this third category of poorly predictable phenomena offer the greatest uncertainties to risk evaluation in nuclear-waste disposal. Alternative techniques, however, such as consequence analysis, subjective probabilities (including expert opinions), sensitivity analysis, or establishing acceptable bounds, may substitute adequately for probability density functions and normal probability estimates.

A flow chart (Figure 1-2) offers a preliminary method for dealing with events and processes in the third group. The flow chart is arranged more-or-less in order of increasing uncertainty and greater undetermined risk. By following the first branch, both uncertainty and risk of a given event or process may be eliminated. For example, the unknown risks associated with raising large volumes of rock to high temperatures might be eliminated by reducing the thermal loading of the repository. Thus a design change may eliminate or reduce the probability of a risk or decrease the uncertainty associated with it. Following the second branch may result in calculation of such a low upper bound on probability that the event ceases to be of concern. The probability of new faulting that would affect the WIPP site in south-eastern New Mexico has been calculated to be less than 4×10^{-11} per year (Claiborne and Gera, 1974). Even if the calculation is in error by a few orders of magnitude, such a small probability removes that event from regulatory concern. As discussed above, the final EPA standard (EPA, 1985) suggests that performance assessments need not consider events that are estimated to have less than one chance in 10,000 of occurring over 10,000 years. Nevertheless, these estimates of probabilities, even though acceptably small, may retain great uncertainty and must be used cautiously.

If risk cannot be eliminated by changing the repository design, and no data that place a low bound on the probability of the event or process exist, then it is appropriate to model the consequences of the event or process of concern. Some events and processes, even if assumed to have a probability of 1, have only a negligible risk because the consequences are very small compared with other possible releases. Appendix B of the final EPA standard (EPA, 1985) suggests that performance assessments need not include events and processes with releases that would not significantly change the estimate of cumulative release.

If consequences are not acceptable, then some estimate of the probability must be obtained. Although it has been determined earlier in the flow chart that data neither exist nor can be obtained in an reasonable amount of time that could be used in calculating or bounding a probability, expert opinion might nevertheless be useful in estimating the probability. Expert opinion should be incorporated in assessments in some probabilistic form, presumably by using Bayesian or Delphi methods. If the probability of some event or process (such as meteorite impact or volcanism in the Gulf Coast) is judged very low by experts, then moderate or high consequences are of small concern, although at this stage in the process, confidence in the predicted results may not be great. If, on the other hand, the probability is judged moderate or large, risk can be calculated using the consequences determined previously and expert judgment of the probability.

Methods of Determining Probabilities

Commonly, the term probability is considered to be synonymous with likelihood and chance; this report uses the term in this sense. Mathematically, the probability of a random event is the limiting value of relative frequency of occurrence reached in an infinitely long sequence of observations of that event. Even though individual outcomes of random events may not be predicted

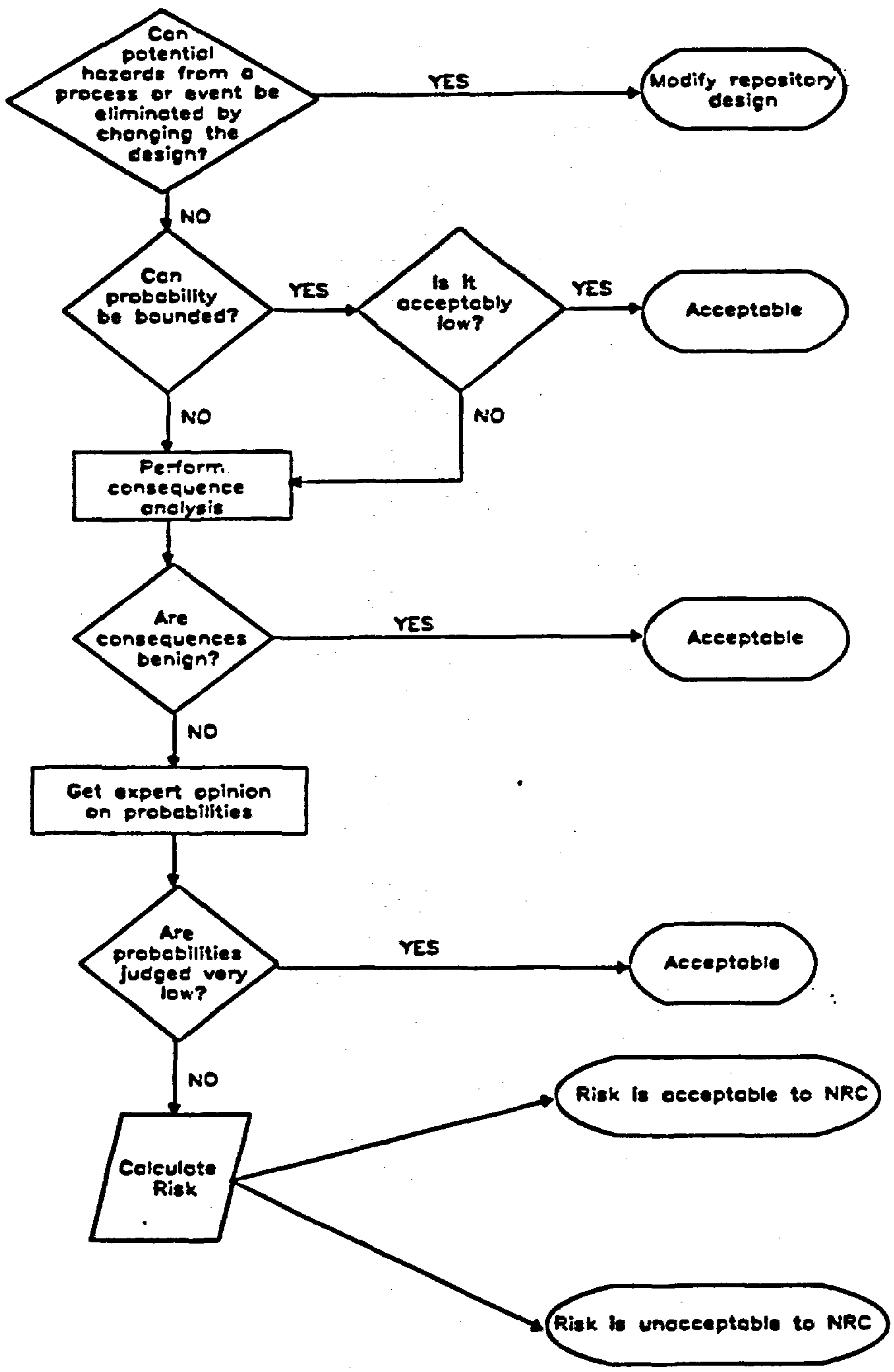


Figure 1-2. A flowchart for dealing with events and processes whose probabilities cannot be determined objectively.

accurately, they will show statistical convergence to a given value over several occurrences or predictions of occurrence. In contrast, individual predictions of other types of events may be made with certainty because they do not behave as random events; these types of phenomena are called deterministic. When initial values of various variables are adequately known, only one result will be realized for deterministic events, and this result can be predicted with complete certainty. Conversely, for random behaving events, even though we know initial parameters adequately, we can predict future events or results only in probabilistic terms; that is, predict only in an ensemble sense, without the ability to predict individual outcomes. Methods for determining probabilities can be divided into axiomatic approaches, frequentist approaches, modeling approaches, and expert judgment. Which of these approaches is most suitable in a particular application depends on the complexity of the system producing the events whose probability is to be determined, how well the system is understood, and the number of data available.

Axiomatic approaches are theoretical in nature. The properties of a system are used to deduce possible outcomes of a trial and the probability of each outcome. For example, in a coin-tossing system, the analyst may determine that there are two possible outcomes, heads and tails. No other outcome seems possible (neglecting the remote possibility that the coin may land on edge). A brief examination of the coin may show that it has no obvious bias. The axiomatic probabilist will therefore determine the probability of heads to be 0.5 and that of tails to be 0.5. Axiomatic approaches have been used to assign relative probabilities to some events and processes of interest to waste management (e.g., Hunter, 1983). The axiomatic approach assumes that the system is well understood; few geological systems are simple enough or well enough understood to make an axiomatic approach practical.

Frequentist approaches depend on the analysis of existing data. Rather than determining what outcomes are possible in a system, frequentist approaches examine what outcomes have been recorded. The nature of the system need not be well understood if data are numerous enough to represent all possible outcomes. Unfortunately, "numerous enough" depends on the system; because the frequentist approach does not require any fundamental understanding of the system, an analyst can never know that one more trial will not produce a new outcome. In a coin-tossing system, the first few data might or might not produce a probability of 0.5 for heads. With three trials, the frequentist would assign a probability of 2/3 to heads, say, and 1/3 to tails. As the number of trials becomes larger, the frequentist normally will record a more equal number of heads and tails, so that the probability would approach 0.5 for heads and for tails. Frequentist approaches have been used in waste management to assign probabilities to occurrences of such events as volcanism (e.g., Crowe and Carr, 1980) and earthquakes of given magnitudes (e.g., Rogers and others, 1977).

Modeling approaches entail developing a model of the system, allowing the system itself to be subjected to numerous trials by proxy. A modeling approach to coin tossing might involve detailed measurements of the weights of various portions of the coin, measurements of forces applied to tossed coins, coin elasticity, and so on. After gathering many data and preparing a computer simulation that incorporates all parameters known or suspected to play a part in determining an outcome, the modeler samples the input data in some way and executes numerous computer runs to determine probability. The modeling approach has been used in waste management in complex computer models such as GSM (Geologic Simulation Model) (Foley and others, 1982).

The use of an axiomatic, frequentist, or modeling approach implicitly assumes that an event or process under consideration is random. Geologic events and processes for the most part are not random phenomena. They differ from truly random occurrences in two major ways. First, geologic phenomena rarely occur repeatedly under identical conditions. Therefore, geologic phenomena rarely, if ever, can constitute an infinitely long sequence from which theoretically correct probabilities could be determined. (For this reason, Bayesian methods may be appropriate in many cases of interest to performance assessment (e.g., Jaynes 1983, p. 163, 176).) In addition, slightly different conditions introduced for each subsequent occurrence of an event or process will generate greater variances than normally would be encountered if randomness and identical conditions truly existed. Second, most scientists would agree that many geologic events and processes actually are deterministic phenomena and could be treated as such if we understood them adequately and had enough information to calculate these deterministic relationships. However, because of complexity in these phenomena and our lack of understanding of true relationships, we must treat many of them as probabilistic phenomena. This is completely satisfactory for scientific and regulatory purposes but it does mean that we do not have as much accuracy and precision as we theoretically could have if they were handled deterministically. In the final performance assessments, however, some expert judgment and irreducible uncertainty will probably be present, necessitating a final decision from the NRC on the acceptability of the residual uncertainty and risk presented by the repository.

The use of expert opinion in assigning probabilities is more subjective and uncertain than the use of axiomatic, frequentist, or modeling approaches, but the EPA standard has explicitly given expert judgment an accepted place in performance assessment. In the absence of adequate data for objective probability determinations, probabilities estimated by experts may be used for performance assessment. Expert opinion may be completely adequate to determine that probabilities are so low than an event is not of regulatory concern, for example. Expert opinion may also be useful when site-specific data are sparse and would be expensive or time-consuming to collect. Finally, great accuracy for a given probability may in many cases be unnecessary if consensus among experts about its possible range exists. Most commonly the basis for these estimates will be empirical Bayesian methods (Efron and Morris, 1973; Morris, 1983) or classical Bayesian methods (Box and Tiao, 1972; Louis, 1984). A disadvantage of all subjective probability determinations, which must be recognized, is that they are subject to manipulation or bias, either deliberately or unknowingly, because each holds varying amounts of individual judgment.

Bayesian probabilistic assessments may provide an evaluation of uncertainty associated with a probability estimate that is superior to that provided by objective probability determinations. This aspect commonly may be deficient in other probability determinations except for those derived from well established edf's or cdf's.

Estimating Probabilities of Geologic Events and Processes

In determining probabilities of geologic events and processes for performance assessments, the question is not whether probabilities can be estimated or assigned to a specific event or process. Invariably probabilities can be and will be estimated, because the EPA standard requires this to be done (EPA, 1985, Section 191.12 (q) and 191.13 (a). Rather, the correct question is "What is the most accurate means available by which realistic probabilities may be determined for an event or process at a specific site?"

As discussed above, probabilities may be estimated and assigned to natural events in various ways; some ways are more desirable than others. In general, objective, physically based probabilities are more satisfactory and more reliable than subjective, or judgmental, probabilities. A spectrum of quantitative measures exist, however, ranging from virtually deterministic predictions with little associated uncertainty, through other objective predictions with increasing degrees of uncertainty or subjective probabilistic assessments with little uncertainty, to other subjective probabilities with associated great uncertainties. The following techniques for estimating probabilities of natural events and processes are discussed in order of generally decreasing preference.

Objective Probability Estimates from Empirical Distribution Functions

Four functions are of interest to the discussion of probabilities of natural events and processes. These are the empirical distribution function (edf), the cumulative distribution function (cdf), the probability density function (pdf), and the complementary cumulative distribution function (ccdf). These four functions will be illustrated using the simple example of a sample of eight cars on a freeway. One car is traveling at a speed of 40 mph; one is traveling at 45 mph; three are traveling at 55 mph; two are traveling at 60 mph; and the last is traveling at 65 mph.

An edf represents actual relative frequencies of sample data less than or equal to a given observation. Its graph is a step function whose steps are of height k/n, $1 \leq k \leq n$, and occur at each observation in a sample of size n. The graph therefore increases from zero to one. It shows the proportion of sample observations $\leq x$ for $-\infty < x < \infty$. The edf for the sample of cars is shown in Figure 1-3a.

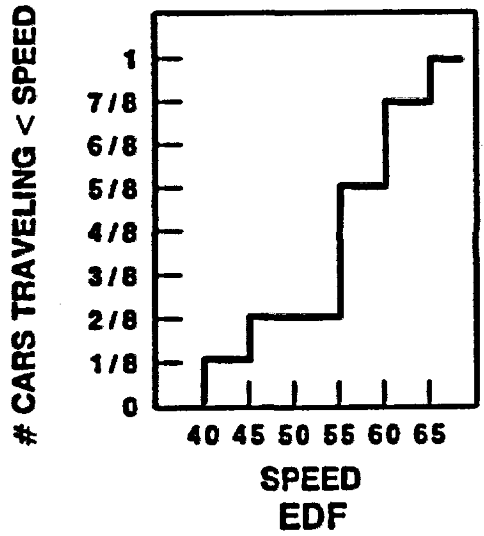
A cdf represents the true probabilities of obtaining observations less than or equal to a given value. Because relative frequencies tend to approximate true probabilities as sample size increases, the edf approximates the cdf as the sample size increases. In the example (Figure 1-3b), the graph of the cdf has been drawn on the assumption that the edf suggests that speeds of cars have a normal distribution. With such a small sample size, there is some uncertainty about the validity of this assumption; for example, a lognormal distribution may fit the data just as well.

A pdf is the first derivative of a cdf, if the cdf is continuous. If the random variable is discrete, the pdf shows the probability of values of the random variable. Roughly speaking, it is a density function that shows the likelihood of getting each value of x. The pdf at x of a continuous random variable X represents the relative rate at which the probability is accumulating in a neighborhood of x. The graph of the pdf in this example (Figure 1-3c) is a bell curve, because the speeds were assumed in the construction of the cdf to be normally distributed.

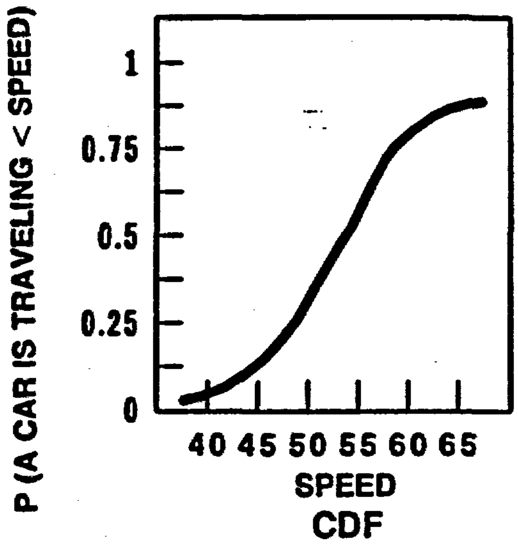
A ccdf is equal to 1 - cdf and represents the probability that a random variable $X > x$. The EPA standard suggests that performance assessment contain complementary cumulative distribution functions (EPA, 1985, Appendix B). The ccdf for this example (Figure 1-3d) shows a probability of 0.5 that any given car will be in violation of the regulatory standard, i.e., the 55 mph speed limit. The sample only showed 3/8 of the cars to be in violation. Either the sample is inadequate or the cdf was poorly chosen.

Empirical Distribution Functions. Cdf's would provide exact probability determinations if they were available. Unfortunately, cdf's are rarely known in real applications: they must be estimated. The estimator for a cdf that is most free of assumptions is an edf derived from geologic data gathered locally. However, local data rarely will be adequate for this purpose and, hence, dependence will normally fall upon generic edf's derived from regional or, less satisfactorily, global data for the same geologic event or process. Generic data are less desirable than local data because geologic conditions rarely, if ever, will be identical for different geologic sites or times.

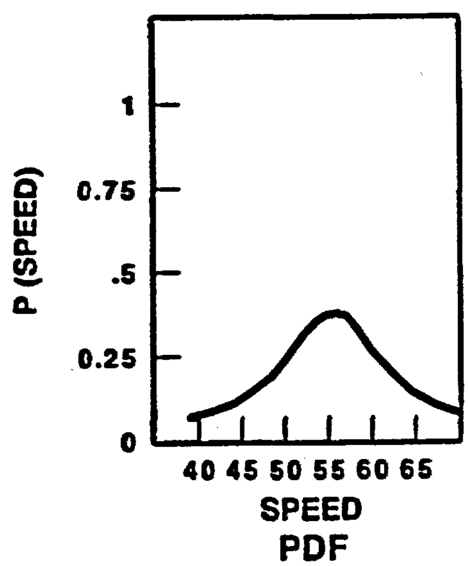
Natural variations in an event or process and observational errors always will be present to some degree in edf data. Whenever local, regional, or global edf's will be the basis for probability estimates, an investigator must decide whether a smoothing equation should be fitted to the edf (a cdf derived inductively) or whether an established family of cdf's (derived deductively) such as lognormal, gamma, negative beta, etc., (Elderton and Johnson, 1969; Johnson and Kotz, 1969, 1970a, 1970b, 1972; Patel and others, 1976) should be fitted to the edf. Many mathematical and geological reasons can be found why a fitted cdf should or should not be substituted for an edf; rarely will the correct course be clear to an investigator. Fortunately, little damage and error will result probably in those cases where one course is not clearly better than another course. Substitution generally is not desirable if observational data fit two or more theoretical cdf's equally well; substitution is essential if one is concerned primarily with prediction of rare events that are represented poorly, or not at all, by available empirical data. Commonly, large or infrequent events are so poorly represented in the geologic record that substitution may be absolutely essential for accurate probabilities. In such a case, the analyst must pay special attention to the tails of the distribution, rather than using a distribution that fits the main central part of the data and extrapolating it to the tails without thought.



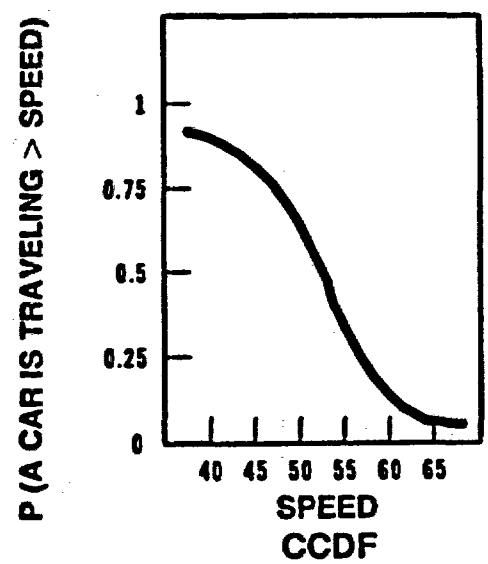
a. Edf for speeds of eight cars, traveling at 40, 45, 55, 55, 55, 60, 60, and 65 mph.



b. Cdf fitted to the edf shown in Figure 1-3a.



c. Pdf derived from the cdf shown in Figure 1-3b, showing the probability that a sampled car will be traveling at a given speed.



d. CCDF derived from the cdf shown in Figure 1-3b, comparing predicted speeds with the 55-mph speed limit.

Figure 1-3. Four mathematical functions used in determining probabilities.

Fitting Curves to EDF Data. Many mathematical techniques have been developed for fitting curves to edf's; some methods are more appropriate than others under various mathematical or geological conditions, and some are totally incorrect under certain conditions. Therefore, care must be taken in deciding which method is to be used in any given case. Similarly, any technique used to determine a cdf or its associated pdf should be clearly described so that others may independently judge its validity for each specific situation.

Classical parametric methods of density estimation assume that certain mathematical conditions exist or are appropriate for data being fitted. These methods include maximum likelihood estimates (Fisher, 1925, 1934, 1974), weighted least squares (Sorenson, 1980), and moments (Pearson, 1902a, 1902b). Conversely, nonparametric techniques for density estimation (Wegman, 1972; Tapia and Thompson, 1978) have fewer mathematical assumptions regarding the form of the density function, but they require large sample sizes. These methods include kernel estimates (Rosenblatt, 1956; Parzen, 1962; Singh, 1977), maximum entropy (Gokhale, 1975; Shore and Johnson, 1980; Gull and Skilling, 1984), projection pursuit (Friedman and Tukey, 1974; Friedman and others, 1984), splines (Boneva and others, 1971; Wahba, 1975), penalized maximum likelihood (Good and Gaskins, 1971); de Montricher and others, 1975), near-neighbor estimates (Loftsgaarden and Quesenberry, 1965), minimum distance (Wolfowitz, 1957; Woodward and others, 1984), incomplete means estimation (Houghton, 1978), orthogonal series (Schwartz, 1967; Wahba, 1971; Brunk, 1978), estimation using Poisson's distribution (Gawronski and Stadtmuller, 1980), and probability weighted moments (Greenwood and others, 1979).

Theoretical Distribution Functions. Lacking an edf or a cdf derived from empirical data, the next best estimate of a pdf or cdf normally will be derived from theoretical considerations based on knowledge of the geologic event or process. For example, seismologists long ago expected theoretically that frequency of seismic events would follow a Poisson distribution because of the nature of these processes (Epstein and Lomnitz, 1966; Cornell, 1971); observational data confirm that to a first-order approximation this is true. Historically, some distributions predicted theoretically have been reasonably close to subsequently observed data distributions; nonetheless, their accuracy directly depends upon our current understanding of a particular geologic event or process. In some instances, knowledge was poor at the time predictions were made, and theoretically derived cdf's have been significantly in error as a result.

Objective Probabilities without Distribution Functions

Often geologic data will be so incomplete that an accurate edf or cdf can not be determined from either available data or our existing knowledge of the event or process. Even so, some estimates of objective probabilities of future occurrences still may be obtained on the basis of extremely limited data. These probability estimates will be objective determinations made without benefit of an edf or cdf. An example commonly encountered in repository performance assessments is frequency of movement along a recent fault; total data obtained from field studies may consist of only two or three values. Uncertainty in these objective probability estimates typically will be great.

Elimination by Consequence Analysis or Bounding

In absence of any probability determinations by either objective or subjective methods noted above, an event or process of concern for performance assessments of repositories possibly may be eliminated from further consideration either through consequence analysis or by establishing bounds on the probability. When an event or process can be shown through either of these techniques to have potential results that are sufficiently insignificant so as to pose no danger to a repository, it may be dismissed from further consideration for purposes of performance assessments.

Subjective Probability Methods

Even for geologic events and processes that neither can be assigned probabilities through normal objective or subjective means nor be elimnated from further consideration by consequence analysis or bounding, additional techniques embodying great uncertainty remain. Subjective probabilites may be established using expert judgment (Kyburg and Smokler, 1980; Uppuluri, 1983) employing several specialists from appropriate fields of geologic knowledge. Great uncertainties invariably are associated with subjective probabilities established in this manner because they represent an ill-defined basis that can not be quantified easily. Each expert's opinion depends upon his state of understanding of an event or process, experience, and abilities, and that similarity which he perceives as existing between the particular geologic situation of concern and other situations that are known and are comparable to varying degrees. In some instances, expert opinion predictions have been shown to provide accurate evaluations whereas in other instances they have been demonstrated to have been poor. Which will be the case for any given probability estimate obtained through expert opinion processes can rarely be assessed satisfactorily at the time those probabilities are assigned.

Closely associated with expert opinion are Delphi methods (Linstone and Turoff, 1975), which use opinions of numerous specialists from a variety of fields obtained by various methods to reach a group consensus on the probability of future events.

Another technique is assigning relative probabilities to events and processes based on general knowledge and individual or group understanding of them. These are subjective, order-of-magnitude estimates (Hunter, 1983). Although relative probabilities will have the greatest uncertainties associated with them and they are the least desirable of all probability assessments, they may be sufficiently informative to be helpful in assessing performance risks.

In summary, the preferred order in which probabilities of geologic events and processes are to be estimated for performance assessments for geologic repositories is

Objective Probabilities Obtained from
- Edf's derived from local observations,
- Edf's derived from regional observations,
- Edf's derived from global observations,
- Pdf's or cdf's derived from theoretical considerations,
- Limited observational data (without benefit of edf or cdf);

Objective Probabilities (Without Distribution Functions) Established by
- Empirical Bayesian methods,
- Bayesian methods,
- Expert judgment;

Elimination of an Event or Process from Further Consideration by
- Consequence analysis,
- Bounding of probabilities;

Subjective Probabilities Established by
- Delphi methods,
- Relative-probability estimation.

For each probability estimate to be used in performance assessments of geologic repositories for nuclear waste, the uncertainty associated with the estimate must be specified. In addition, the basis for both probability and uncertainty estimates and the methods by which they were obtained must be stated clearly and explicitly so that others are able to freely evaluate the validity of each probability and uncertainty estimate.

Even such ill-defined probabilities as these generated subjectively may be adequate for some parts of the performance assessment, for example, where the estimated probability is very small or large.

Analysis of Uncertainties

A probability is a mathematical expression that embodies uncertainty about the future by definition: some workers believe that to refer to the "uncertainty in a probability" is to misunderstand probability altogether. For most of the phenomena treated here, however, it is impossible to determine probabilities by the method of repeated identical trials. Rather, the probabilities must be calculated using data that are uncertain in the usual sense, that is, the exact value of a given parameter is unknown because of, say, measurement error. It is in this sense that we refer to uncertainty in probabilities in this report. Uncertainty in the probabilities may arise from two sources. First, the physical model may be inaccurate. For example, volcanism might be modeled as a spatially random process, even though it is known to be controlled by deep-seated crustal weaknesses. If the location of crustal weaknesses is unknown, spatial randomness may be the best model available, but still it is not the correct model. Second, there may be uncertainty about the values of parameters used to calculate the probabilities. For example, the probability of volcanism in a given area might be calculated based in part on the ages of existing volcanoes. Radiometric ages used to date volcanism always carry some uncertainty. The EPA standard requires some estimate of the uncertainty in the probabilities of risks from proposed repositories.

Methods for Combining Uncertainties

The treatment of uncertainties in performance assessments involves a complex model of physical processes, which in turn consists of several sub-models, each somewhat autonomous, and each characterized by inputs and outputs. Inputs may be known parameter values, estimates of unknown parameter values, or random quantities whose probability distribution may be known or estimated. Outputs of a sub-model may serve as inputs to other sub-models, and therefore the probability distribution of each output must be known or estimated. Alternatively, outputs of a sub-model may go directly into determining the probability distribution of release of radionuclides into the environment.

For regulatory purposes, the latter probability distribution need not be known entirely. It is necessary only to determine whether the probabilities associated with two known quantities are less than 0.1 and 0.001 respectively. In order to determine probabilities associated with those two quantities, however, the entire probability distributions of all preceeding inputs and outputs must be known or estimated. Several methods have been proposed for combining uncertainties associated with inputs of the various sub-models in order to achieve the desired estimates of released quantities. Some methods are discussed briefly here. One or more recent papers are cited for each method. Iman and Helton (1985) thoroughly compared some properties of several of these methods and included an extensive bibliography.

Monte Carlo. A Monte Carlo approach repeatedly selects values from the range of values possible for each input variable or parameter, using some random procedure, and uses those values as inputs in the model to find corresponding output values (Cranwell, Campbell, and others, 1982; Martz and others, 1983). Repeated sampling and random selection of inputs characterize the Monte Carlo procedure. Several popular procedures for selecting input values include simple random sampling, stratified sampling, and Latin Hypercube Sampling (McKay and others, 1979).

One asset of the Monte Carlo procedure is its flexibility, enabling sub-models to be combined, outputs from one model to be used as inputs to another model, and even the establishment of a pseudo-correlation among input variables in order to provide a more realistic model (Iman and Conover, 1982). Another asset is that the entire cdf of the output may be estimated, and bounds on the estimate may be obtained (Iman and Conover, 1980). A disadvantage is that the accuracy of a Monte Carlo procedure depends upon sufficient numbers of simulations and upon accurately knowing the probability distributions for each random procedure.

Maximus. If components in a model are "go-no go" in nature, such as "fault-no fault" or "breakdown-no breakdown", the Maximus method can be used to estimate the probability of system failure (Maximus, Inc., 1980). This procedure is easy to use and has been shown to be accurate when compared with exact results in those simple systems that have exact results. The Maximus method also provides an apparently accurate confidence interval for the probability of system failure (Spencer and Easterling, 1984).

Spencer and Easterling (1984) suggested a method for separating the influence of subjective probability estimates from objective probability estimates in models where Maximus could be used. If the reliability parameters of the components follow known distributions, Bayesian procedures may be used to provide more accurate estimates of the system failure probabilities (Iman and Helton, 1985).

Adjoint. The adjoint procedure propagates a "typical" point through the model to obtain a "typical" output. The definition of typical output may vary from case to case and may be the mean, median, mode, or some other selected parameter value of each input variable. The output variable is analyzed, along with all partial derivatives of the output variable, taken with respect to input variables at the single output value observed (Cacuci and others, 1983; Dacol and Rabitz, 1983). Partial derivatives are obtained by an analysis of the entire model. The single output value and partial derivatives may be used to form a regression model that is sampled extensively to obtain an estimate of the cdf of the output variable (Lewins and Becker, 1982).

The adjoint method provides biased results that depend strongly on the choice of "typical" input values. The method was intended to provide a sensivity analysis for models that can be expressed as systems of nonlinear differential equations, and its extension to estimate output probabilities is difficult to justify. Also, the regression model obtained using the adjoint procedure may be a poor likeness of the original model, especially outside the region of a single observation.

Factorial Designs. The theory of statistical factorial designs can be used to select input values for a model (Campbell and others, 1980). A regression equation is fitted to the input and output variables, and a Monte Carlo simulation on the regression model provides an estimate of the output cdf (Iman and others, 1978). If there are many input variables in the model, a fractional factorial design must be used in order to keep the number of runs moderate.

This procedure uses classical statistical procedures that are easily understood and readily available; however, it becomes prohibitively difficult when the number of input variables is even moderately large. Also, the cdf obtained for the final analysis is accurate for the regression surface, but may not be accurate for the more realistic original model that is essentially replaced by the much simpler regression model. Iman and Helton (1985) illustrated this procedure.

Bayesian. Bayesian methods combine prior subjective information about the probable value of some parameter with objective information in the form of observed values of the random process using the parameter, in order to obtain better estimates of the probable value of the parameter. Bayesian procedures can be used to combine subjective information with objective information to obtain probability distributions for model inputs, where those inputs are parameters (Martz and Waller, 1982). Controversy arises whenever parameters whose values are fixed but unknown are treated like random variables, whose values are not fixed. However, Bayesian methods are useful in applied work, and should be permitted in this important application.

Input distributions, however obtained, may be sampled using Monte Carlo methods and treated in the usual way.

Summary

This report discusses a number of techniques for calculating or estimating probabilities of various events or processes that might occur during the lifetime of a high-level radioactive waste repository situated deep beneath Earth's surface. Most of these events only have a very small likelihood of occurring during the next 10,000 years or even 100,000 or 1,000,000 years, but cannot be excluded based on what we now know. In order to understand whether the performance of the repository will be degraded by the possible occurrence of any of these events or processes, the best available probability estimates must be provided. However, each event or process is really a category of events of different sizes and different severities. Therefore, it is necessary to have not only an overall estimate of the probability, but also a disaggregated estimate of the likelihood of various severities, recognizing that for each category under consideration the more severe events will probably be less likely to occur than events of lesser severity.

Inputs needed to make probabilistic assessments presented in this report do not differ in principle from those needed for any other type of analytical method. The analyst requires a model of the phenomena under consideration, applicable data, a method for estimating uncertainties, and a means of explaining how the analysis was done so that it can be repeated and checked by others.

There are important limitations inherent in the types of analyses discussed in this report. Perhaps the most important limitation stems from the character of the phenomena being studied--specifically, many are so rare that no way to validate the calculations by any actual experiments or experience is known. In this sense, the analyses will always be subject to varying opinions about the validity of the input information or the models used, and there will always be varying interpretations as to the meaning of the calculated results.

Although the analytical methods under discussion are inherently quantitative in character, most of the broad conclusions are qualitative. This fact is not, of course, an artifact of probabilistic methodologies, but rather is an intrinsic characteristic of the issues being studied.

Because our experience is only limited, the probability estimates cannot be based on experience data alone (such as an actual recorded number of volcanic events). Rather, they must be based on some combination of experience and analysis, specifically a combination of inferences based on the limited knowledge we do have, laboratory experiments, and theoretical considerations.

Inevitably, probability estimates will have uncertainties, and in many areas under study these uncertainties will be large. Whether the results of these calculations can be used as a basis for decision-making despite the large uncertainties is a question that cannot, of course, be addressed except on a case-by-case basis. It would be incorrect, however, to dismiss the results of these calculations without careful analysis of the decision(s) that are affected by them.

References

Arnett, R. C., R. G. Baca, J. A. Caggiano, S. M. Price, R. E. Gephart, and S. E. Logan, 1980, Preliminary Hydrologic Release Scenarios for a Candidate Repository Site in the Columbia River Basalts, RHO-BWI-ST-12, Rockwell Hanford Operations, Richland, WA.

Berrill, J. B., and R. D. Davis, 1980, "Maximum Entropy and the Magnitude Distribution," Bull. Seismol. Soc. Amer., vol. 70, p. 1823-1831.

Bingham, Felton W., and George E. Barr, 1979, Scenarios for Long-Term Release of Radionuclides From a Nuclear-Waste Repository in the Los Medanos Region of New Mexico, SAND78-1730, Sandia Laboratories, Albuquerque, NM, 90 pp.

Boneva, L. I., D. G. Kendall, and I. Stefanov, 1971, "Spline Transformations," Jour. Royal Stat. Soc., Ser. B, vol. 33, p. 1-70.

Box, G. E. P., and G. C. Tiao, 1972, Bayesian Inference in Statistical Analysis, Addison-Wesley, Reading, MA.

Brunk, H. D., 1978, "Univariate Density Estimation by Orthogonal Series," Biometrika, vol. 65, p. 521-528.

Cacuci, D. G., P. J. Maudlin, and C. U. Parks, 1983, "Adjoint Sensitivity Analysis of Extremum-Type Responses in Reactor Safety," Nuclear Sci. Engineering, vol. 83, p. 112-135.

Campbell, J. E., R. L. Iman, and M. Reeves, 1980, Risk Methodology for Geologic Disposal of Radioactive Waste: Transport Model Sensitivity Analysis, NUREG/CR-1377, SAND80-0644, Sandia National Laboratories, Albuquerque, NM.

Carr, T. R., 1982, "Log-linear Models, Markov Chains, and Cyclic Sedimentation," Jour. Sedimentary Petrology, vol. 52, p. 905-912.

Claiborne, H. C., and F. Gera, 1974, Potential Containment Failure Mechanisms and Their Consequences at a Radioactive Waste Repository in Bedded Salt in New Mexico, ORNL-TM-4639, Oak Ridge National Laboratory, Oak Ridge, TN.

Clifton, H. E., 1978, "Storms, Floods and the Coastal Sedimentary Record," (abstr.), Amer. Assoc. Petroleum Geologists Research Colloquium, Oklahoma City.

Cornell, C. A., 1971, "Probabilistic Analysis of Damage to Structures under Seismic Loads," in D. A. Howells, I. P. Haigh, and C. Taylor, eds., Dynamic Waves in Civil Engineering, John Wiley and Sons, London.

Cranwell, R. M., J. E. Campbell, J. C. Helton, R. L. Iman, D. E. Longsine, N. R. Ortiz, G. E. Runkle, and M. J. Shortencarier, 1982, Risk Methodology for Geologic Disposal of Radioactive Waste: Final Report, NUREG/CR-2452, SAND81-2573, Sandia National Laboratories, Albuquerque, NM.

Cranwell, R. M., R. V. Guzowski, J. E. Campbell, N. R. Ortiz, 1982, Risk Methodology for Geologic Disposal of Radioactive Waste: Scenario Selection Procedure, NUREG/CR-1667, SAND82-1429, Sandia National Laboratories, Albuquerque, NM, 153 pp.

Crowe, B. M., and W. J. Carr, 1980, Preliminary Assessment of the Risk of Volcanism at a Proposed Nuclear Waste Repository in the Southern Great Basin, US Geological Survey Open-file Report 80-357.

Dacol, D. K., and H. Rabitz, 1983, "Arbitrary Order Functional Sensitivity Densities for Reaction-Diffusion Systems," Jour. Chem. Phys., vol. 78, p. 4905-4914.

Davis, S. N., and R. J. M. DeWiest, 1966, Hydrogeology, John Wiley and Sons, New York, 447 pp.

de Montricher, G. F., R. A. Tapia, and J. R. Thompson, 1975, "Nonparametric Maximum Likelihood Estimation of Probability Densities by Penalized Function Methods," Annals Stat., vol. 3, p. 1329-1348.

DeWiest, R. J. M., ed., 1969, Flow Through Porous Media, Academic Press, New York, 516 pp.

Efron, Bradley, and Carl Morris, 1973, "Stein's Estimation Rule and Its Competitions--An Empirical Bayes Approach," Jour. Amer. Stat. Assoc., vol. 68, p. 117-130.

Elderton, William Palen, and Norman Lloyd Johnson, 1969, Systems of Frequency Curves, Cambridge Univ. Press, Cambridge.

Epstein, B., and C. Lomnitz, 1966, "A Model for the Occurrence of Large Earthquakes," Nature, vol. 211, p. 954-956.

Fisher, R. A., 1925, "Theory of Statistical Estimation," Proc. Camb. Phil. Soc., vol. 22, p. 700-725.

Fisher, R. A., 1934, "Two New Properties of Mathematical Likelihood," Proc. Royal Soc., Ser. A, vol. 144, p. 285-307.

Fisher, R. A., 1974, Statistical Methods and Scientific Inference, Oliver and Boyd, Edinburgh, 3rd ed.

Foley, M. G., G. M. Petrie, A. J. Baldwin, and R. G. Craig, 1982, Geologic Simulation Model for a Hypothetical Site in the Columbia Plateau: Volume 2: Results, PNL-3542-2, Battelle Pacific Northwest Laboratory, Richland, WA.

Friedman, Jerome H., and John W. Tukey, 1974, "A Projection Pursuit Algorithm for Exploratory Data Analysis," IEEE Trans. Computers, C-23, p. 881-890.

Friedman, Jerome H., Werner Stuetzle, and Anne Schrodder, 1984, "Projection Pursuit Density Estimation," Jour. Amer. Stat. Assoc., vol. 79, p. 599-608.

Gawronski, Wolfgang, and Ulrich Stadtmuller, 1980, "On Density Estimation by Means of Poisson's Distribution," Scand. Jour. Stat., vol. 7, p. 90-94.

Gokhale, D. V., 1975, "Maxiumum Entropy Characterizations of Some Distributions," in G. P. Patel and others, eds., Statistical Distributions in Scientific Work, D. Reidel Publ. Co., Dordrecht, Holland, p. 299-304.

Good, I. J., and R. A. Gaskins, 1971, "Nonparametric Roughness Penalties for Probability Densities," Biometrika, vol. 58, p. 255-277.

Greenwood, J. Arthur, J. Maciunas Landwehr, N. C. Matalas, and J. R. Wallis, 1979, "Probability Weighted Moments: Definition and Relation to Parameters of Several Distributions Expressable in Inverse Form," Water Resources Research, vol. 15, p. 1049-1054.

Gretner, P. E., 1967, "Significance of the Rare Event in Geology," Bull. Amer. Assoc. Petroleum Geologists, vol. 60, p. 2197-2206.

Gull, S. F., and J. Skilling, 1984, "The Maximum Entropy Method," in J. A. Roberts, ed., Indirect Imaging, Cambridge Univ. Press, Cambridge, p. 267-279.

Harwell, M. A., S. K. Gupta, A. Brandstetter, C. C. Harwell, G. L. Benson, B. A. Napier, J. R. Raymond, A. E. Reisenauer, D. J. Bradley, L. S. Prater, R. J. Serne, C. S. Simmons, J. K. Soldat, D. L. Strenge, C. R. Cole, J. F. Washburn, W. J. Deutsch, and J. T. Zellmer, 1982, Reference Site Initial Assessment for a Salt Dome Repository, Volume 1, PNL-2955 Vol. 1, Pacific Northwest Laboratory, Battelle Memorial Institute, Richland, WA.

Houghton, John C., 1978, "The Incomplete Means Estimation Procedure Applied to Flood Frequency Analysis," Water Resources Research, vol. 14, p. 1111-1115.

Hunter, Regina L., 1983, Preliminary Scenarios for the Release of Radioactive Waste From a Hypothetical Repository in Basalt of the Columbia Plateau, NUREG/CR-3353, SAND83-1342, Sandia National Laboratories, Albuquerque, NM, 75 pp.

Hunter, R. L., G. E. Barr, and F. W. Bingham, 1983, Scenarios for Consequence Assessments of Radioactive-Waste Repositories at Yucca Mountain, Nevada Test Site, SAND82-1227, Sandia National Laboratories, Albuquerque, NM.

Hunter, R. L., C. John Mann, and R. M. Cranwell, 1985, "Determining Probabilities of Geologic Events and Processes," Proc. Internat. Topical Meeting on High-Level Nuclear Waste Disposal, September 24-26, 1985, Pasco, WA.

Iman, Ronald L., and W. J. Conover, 1980, "Small Sample Sensitivity Analysis Techniques for Computer Models with an Application to Risk Assessment," Comm. Stat.-Theor. Meth., vol. A9(17), p. 1749-1842.

Iman, R. L., and W. J. Conover, 1982, "A Distribution-Free Approach to Inducing Rank Correlation Among Input Variables", Communications in Stat., B11(3), p. 311-334.

Iman, R. L., and J. C. Helton, 1985, A Comparison of Uncertainty and Sensitivity Analysis Techniques for Computer Models, NUREG/CR-3904, SAND84-1461, Sandia National Laboratories, Albuquerque, NM.

Iman, R. L., J. C. Helton, and J. E. Campbell, 1978, Risk Methodology for Geologic Disposal of Radioactive Waste: Sensitivity Analysis Techniques, NUREG/CR-0394, SAND78-0912, Sandia Laboratories, Albuquerque, NM.

Jaynes, E. T., 1983, "Confidence Intervals vs. Bayesian Intervals," in R. D. Rosenkrantz, ed., E. T. Jaynes: Papers on Probability, Statistics, and Statistical Physics, D. Reidel Publishing Company, Dordrecht, Holland, 434 pp.

Johnson, Norman L., and Samuel Kotz, 1969, Discrete Distributions, Houghton Mifflin Co., Boston, 323 pp.

Johnson, Norman L., and Samuel Kotz, 1970a, Continuous Univariate Distributions--1, Houghton Mifflin Co., Boston.

Johnson, Norman L., and Samuel Kotz, 1970b, Continuous Univariate Distributions--2, Houghton Mifflin Co., Boston, 301 pp.

Johnson, Norman L., and Samuel Kotz, 1972, Distributions in Statistics: Continuous Multivariate Distributions, John Wiley and Sons, Inc., New York, 308 pp.

Kyburg, Henry E., Jr., and Howard E. Smokler, 1980, Studies in Subjective Probability, Robert E. Krieger Publ. Co., Huntington, NY, 257 pp.

Lewins, J., and M. Becker, eds., 1982, "Sensitivity and Uncertainty Analysis of Reactor Performance Parameters," Adv. Nuclear Sci. and Technology, 14, Plenum Press, New York.

Linstone, Harold A., and Murray Turoff, 1975, The Delphi Method Techniques and Applications, Addison-Wesley Publ. Co., Reading, MA, 614 pp.

Loftsgaarden, D. O., and C. F. Quesenberry, 1965, "A Nonparametric Estimate of a Multivariate Density Function," Annals Math. Stat., vol. 36, p. 1049-1051.

Louis, Thomas A., 1984, "Estimating a Population of Parameter Values Using Bayes and Empirical Bayes Methods," Jour. Amer. Stat. Assoc., vol. 79, p. 393-398.

Marle, C. M., 1981, Multiphase Flow in Porous Media, Gulf Publ. Co., Houston, TX, 254 pp.

Martz, H. F., and R. A. Waller, 1982, Bayesian Reliability Analysis, John Wiley and Sons, Inc., New York.

Martz, H. F., R. J. Beckman, K. Campbell, D. E. Whiteman, and J. M. Booker, 1983, A Comparison of Methods for Uncertainty Analysis of Nuclear Power Plant Safety System Fault Tree Models, NUREG/CR-3263, LA-9729-MS, Los Alamos National Laboratory, Los Alamos, NM.

Maximus, Inc., 1980, "Handbook for the Calculation of Lower Statistical Confidence Bounds on System Reliability," Unpublished manuscript.

McKay, M. D., W. J. Conover, and R. J. Beckman, 1979, "A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output From a Computer Code," Technometrics, vol. 21, p. 239-245.

Morris, Carl N., 1983, "Parametric Empirical Bayes Inference: Theory and Application," Jour. Amer. Stat. Assoc., vol. 78, p. 47-65.

Parzen, E., 1962, "On the Estimation of a Probability Density Function and the Mode," Annals Math. Stat., vol. 33, p. 832-837.

Patel, Jagdish K., C. H. Kapakia, and D. B. Owen, 1976, Handbook of Statistical Distributions, Marcel Dekker, Inc., New York, 294 pp.

Patwardhan, A. S., R. B. Kulkarni, and D. Tocher, 1980, "A Semi-Markov Model for Characteristic Recurrence of Great Earthquakes," Bull. Seismol. Soc. Amer., vol. 70, p. 323-347.

Pearson, Karl, 1902a, "On the Systematic Fitting of Curves to Observations and Measurements," Biometrika, vol. 1, p. 265-303.

Pearson, Karl, 1902b, "On the Systematic Fitting of Curves to Observations and Measurements, Part II," Biometrika, vol. 2, p. 1-23.

Pepping, R. E., M. S. Y. Chu, and M. D. Siegel, 1983, Technical Assistance for Regulatory Development: A Simplified Repository Analysis in a Hypotheti-Bedded Salt Formation, SAND82-0996, Sandia National Laboratories, Albuquerque, NM.

Rantz, S. E., 1964, "Surface Water Hydrology of Coastal Basins of Northern California," US Geological Survey Water Supply Paper 1758.

Rogers, A. M., D. M. Perkins, and F. A. McKeown, 1977, "A Preliminary Assessment of the Seismic Hazard of the Nevada Test Site Region," Bull. Seismol. Soc. Amer., vol. 67, p. 1587-1606.

Rosenblatt, Murray, 1956, "Remarks on Some Nonparametric Estimates of a Density Function," Annals Math. Stat., vol. 27, p. 832-837.

Sadler, P. M., 1981, "Sediment Accumulation Rates and the Completeness of Stratigraphic Sections," Jour. Geology, vol. 89, p. 569-584.

Schwartz, S. C., 1967, "Estimation of a Probability Density by an Orthogonal Series," Annals Math. Stat., vol. 38, p. 1261-1265.

Shakal, A. F., and D. E. Willis, 1972, "Estimated Earthquake Probabilities in the North Circum-Pacific Area," Bull. Seismol. Soc. Amer., vol. 62, p. 1397-1410.

Shore, John E., and Rodney W. Johnson, 1980, "Axiomatic Derivation of the Principle of Maximum Entropy and the Principle of Minimum Cross-Entropy," IEEE Trans. Information Theory, vol. IT-26, p. 26-37.

Simpson, George Gaylord, 1952, "Probabilities of Dispersal Through Time," Bull. Amer. Museum Natural History, vol. 99, p. 163-176.

Singh, R. S., 1977, "Improvement on Some Known Nonparametric Uniformly Consistent Estimators of Derivatives of a Density," Annals Stat., vol. 5, p. 394-399.

Sorenson, Harold W., 1980, Parameter Estimation, Principles and Problems, Marcel Dekker, Inc., New York, 375 pp.

Spencer, F. W., and R. G. Easterling, 1984, Lower Confidence Bounds on System Reliability Using Component Data: The Maximus Methodology, SAND84-1199C, Sandia National Laboratories, Albuquerque, NM.

Tapia, Richard A., and James R. Thompson, 1978, Nonparametric Probability Density Estimation, Johns Hopkins Univ. Press, Baltimore, 171 pp.

US Environmental Protection Agency, 1985, "Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes, Final Rule," 40 CFR Part 191, Federal Register, vol. 50, p. 38066-38089.

US Nuclear Regulatory Commission, 1983, "Disposal of High-Level Radioactive Wastes in Geologic Repositories, Technical Criteria, Final Rule," 10 CFR Part 60, Federal Register, vol. 48, p. 28194-28229.

US Nuclear Regulatory Commission, 1984, Probabilistic Risk Assessment (PRA): Status Report and Guidance for Regulatory Application, NUREG-1050, US Nuclear Regulatory Commission, Washington, DC.

Uppuluri, U. R. R., 1983, Expert Opinion and Ranking Methods, NUREG/CR-3115, ORNL/CSD/TM-201, Union Carbide Corp., Oak Ridge, TN, 20 pp.

Wahba, Grace, 1971, "A Polynomial Algorithm for Density Estimation," Annals Math. Stat., vol. 42, p. 1870-1886.

Wahba, Grace, 1975, "Interpolating Spline Methods for Density Estimation, I: Equispaced Knots," Annals Stat., vol. 3, p. 30-48.

Wegman, E. J., 1972, "Nonparametric Density Estimation, I. A Summary of Available Methods," Technometrics, vol. 14, p. 533-546.

Williams, H., and A. R. McBirney, 1979, Volcanology, Freeman, Cooper, and Co., San Francisco, CA, 400 p.

Wolfowitz, J., 1957, "The Minimum Distance Method," Annals Math. Stat., vol. 28, p. 75-88.

Woodward, Wayne A., William C. Parr, William R. Schucany, and Hildegard Lindsey, 1984, "A Comparison of Minimum Distance and Maximum Likelihood Estimation of a Mixture Proportion," Jour. Amer. Stat. Assoc., vol. 79, p. 590-598.

Chapter 2

RESOURCE EXPLORATION*

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Abstract

Probability trees (also known as event trees) are useful in analyzing the interdependent relationships between human and geological factors as they affect estimates of the probability of intersection of HLW repository sites by exploratory boreholes in the future. The trees reveal that human factors have large influence and cannot be ignored. Procedures for objectively estimating the occurrence of mineral commodities in proposed repository sites are difficult to apply, and adequate data are not available. Most critically, even if probability distributions for occurrence of mineral deposits in the vicinity of a repository site could be generated, probability distributions for the number of boreholes that future explorationists would need to discover these deposits are difficult or impossible to estimate.

Introduction

This chapter considers procedures for estimating probabilities of breaching of HLW repositories by resource exploration or exploitation activities within the next 10,000 years. "Resource exploration or exploitation activities" here means any action, such as drilling boreholes or sinking shafts, in the search for mineral commodities. "Mineral commodity" means any material commodity extracted from Earth's crust, including oil and natural gas, coal, metals, and nonmetallic materials of all sorts, including salt, clay, stone, and so forth. In addition, geothermal energy, either in the form of steam or hot water or as "dry heat," could be included as a mineral or "extractable" commodity, although this chapter generally ignores geothermal energy. Ground water in the usual sense (i.e., potable water at ambient temperatures at relatively shallow depths) is excluded as a mineral commodity. However, ground water in the form of brines, or even of waters of relatively low salinity, is included as mineral commodities if at depths generally below those at which potable ground water is extracted, and if they are potentially valuable for their dissolved solids.

Exploitation activity in the form of drilling disposal wells (e.g., wells for disposal of brines produced in oil wells) might or might not be included in exploration or exploitation activity. Disposal wells are not included

*This chapter reviews and evaluates techniques for assigning probabilities to future exploration for resources. This review and evaluation does not imply that the NRC has endorsed the used of the techniques discussed here.

because the emphasis in this review is on activities that pertain to exploration, in contrast to exploitation. However, exploration and exploitation are part of a continuum, with no well-defined distinction between them.

Limits on what sets a mineral commodity apart from a "noncommodity" are desirable. Concentration at some specified multiple of ambient or background concentration has been suggested as necessary to the definition. Such a definition may be acceptable for metallic ore deposits (e.g., gold and iron), but such a definition is not generally applicable to nonmetallic deposits, whose value may depend upon aesthetic qualities (e.g., precious and semiprecious stones) or upon chemical quality and volume (e.g., limestone). At least one mineral commodity (employing my earlier definition) is universally present in the crust, namely, dry heat.

Specific objectives of this review are

1. To define the context in which probabilities attached to mineral resource exploration and exploitation are interdependent with other probabilistic elements and to represent these interdependent relationships with "probability trees."

2. To consider the extent to which procedures are available that would permit frequencies, and in turn probabilities, to be assigned to the presence, volume, and grade of mineral commodities in segments of Earth's crust proximate to proposed HLW repositories.

3. To review procedures that might permit probabilities attached to future exploratory drilling to be estimated. These probabilities should be conditional upon predicted mineral commodities and should be expressed on a unit-area basis.

Regulatory Guidance

Potential disruptions of a repository as a result of resource exploration differ from other geologic processes and events in that the EPA and NRC offer specific regulatory guidance that may be applied in assigning their probabilities.

The EPA (1985, p. 38077a) does not think that developing a "correct" estimate of the probability of inadvertent human intrusion is possible, and therefore the Agency has limited the severity of the assumptions to be used in performance assessments. The EPA Standard (EPA, 1985, Appendix B), suggests implementing agencies can assume that intruders will soon detect or be warned of the existence of the repository. In addition, the EPA offers specific rates of inadvertent intrusion that need not be assumed in the performance assessment to be exceeded. The rates are 30 boreholes/km^2 of repository area per 10,000 years, for repositories in or near sedimentary rocks, and 3 boreholes/km^2 of repository area per 10,000 years, for repositories in other rocks. (Appendix B also sets upper bounds on the consequences that should be assumed.) For facilities not regulated by the NRC, Section 191.14 requires permanent markers and records to indicate the location of the waste and its dangers.

In its definition of "unanticipated processes and events," the NRC Regulation (NRC, 1983) limits the assumptions that can be made in developing scenarios on human intrusion for the performance assessment. Indirectly, this definition applies to the probabilities that might be assigned to human intrusion. Human intrusion "may only be found to be sufficiently credible to warrant consideration if it is assumed that" effective monuments have been emplaced; future values of resources can be adequately assessed today; society has retained an understanding of radioactivity; society will be at least as effective in alleviating the risks caused by the intrusion as it was in causing them; and relevent records remain available for at least several hundred years (NRC, 1983, p. 28218c). Performance assessments need not consider or assign probabilities to human-intrusion scenarios that assume, for example, breakdown of society and loss of records or a loss of the technology useful in recognizing radiation. A scenario that might be considered would be a totally inadvertent intrusion that results from a combination of otherwise innocuous circumstances, such as the flooding of a salt mine through an exploratory gas borehole that occurred in Louisiana (Gold, 1981).

The required assumptions bear directly on the subjective probabilities to be assigned to the first few branches of the basic tree discussed immediately below. This discussion focuses on the theoretical basis for probabilities that <u>might</u> be assigned; however, the wording of the EPA Standard and NRC Regulation significantly limit the probabilities that <u>may</u> be assigned in a performance assessment.

The Basic Tree of Interdependent Probabilities

The probability that a HLW repository will be breached by exploration activity should be considered in context with other chance events with which it is interdependent. "Probability trees," which are also known as "event trees," are well suited to show such relationships. A probability tree is a diagram of a sequence of chance events. The sequence is generally diagrammed so that events are shown in succession from left to right. Complementary probabilities, which must sum to 1.0, pertain to branches stemming from each fork. The branches fork repeatedly at "chance forks," finally terminating at the tips of branches. Each branch tip thus represents a terminal event. The probability of reaching a specific tip or terminal event can be calculated by progressively working from the trunk of the tree to the tip, or vice versa, multiplying probabilities attached to the specific branch followed at each of the forks. The multiplicative probabilities attached to all routes that lead to tips must sum to 1.0, provided that all possible branches are included. The probability of reaching a particular terminal event, such as breaching of a repository, can be calculated by summing all the multiplicative probabilities attached to branch tips that represent that terminal event.

Trees may vary in complexity. A simple tree may represent gross probabilistic relationships, but the same basic tree can be expanded, ad infinitum, to represent probabilistic relationships at any level of detail.

A basic tree showing breaching of HLW repositories by all possible alternatives is shown by Figure 2-1. Of the six terminal events shown, three involve breaching of the repository by exploration. Of these three, two are deliberate and one is inadvertent. The probability of breaching thus is calculated by multiplying the probabilities attached to each branching sequence that leads to breaching as a terminal event, and summing those that terminate in breaching.

The probability of breaching can be calculated only if probabilities are assigned to each branch. Thus, probabilities must be assigned to all branches that involve deliberate or careless breaching of a repository (Figure 2-1, branches (e) and (g)). Although assigning such probabilities may be protested as futile, we nevertheless must set each at some value to evaluate the tree. Of course, we can set each at some small value, even at zero. Setting values for "deliberate-breach" branches is a matter of subjective judgment, because objective data do not exist by which these may be estimated.

Two separate situations exist in which exploration activity is critical (Figure 2-1). In branch (c), knowledge of a repository that had been previously lost, as represented by branch (a), is regained using geophysical techniques. Objective procedures for estimating the probability to be assigned to branch (c) seem impossible to devise. Thus, like the probability of branch (a) that knowledge of a repository will be lost, the probability for branch (c) will be largely subjective, involving assumptions as to the efficacy of geophysical and geochemical procedures in the distant future. The other situation involves branch (i), in which a repository is unknown and is inadvertently breached in exploration.

One ameliorating factor may be the availability of estimates of the likelihood that repository sites will have physical, chemical, or biological manifestations at or near the surface. For example, will increases in heat flow or radioactivity indicate the presence of a repository? These are matters for repository engineers to consider, and the "knowledge-regained-by-geophysics" issue is not pursued further here.

Now, let us consider branch (d), which involves failure to detect the repository site by geophysics or geochemistry in advance of drilling. The subbranches involve either inadvertent breaching by exploration (i), or not breaching (j). We can detach branch (d) and its subbranches and focus on them, excluding the rest of the tree. The probability attached to branch (d) is the complement of branch (c). The two sum to 1.0, and one necessarily determines the other. Because branch (c) appears to be indeterminate by objective methods, branch (d) is likewise indeterminate, and the probability attached to (d) apparently will have to be assigned as a matter of subjective judgment.

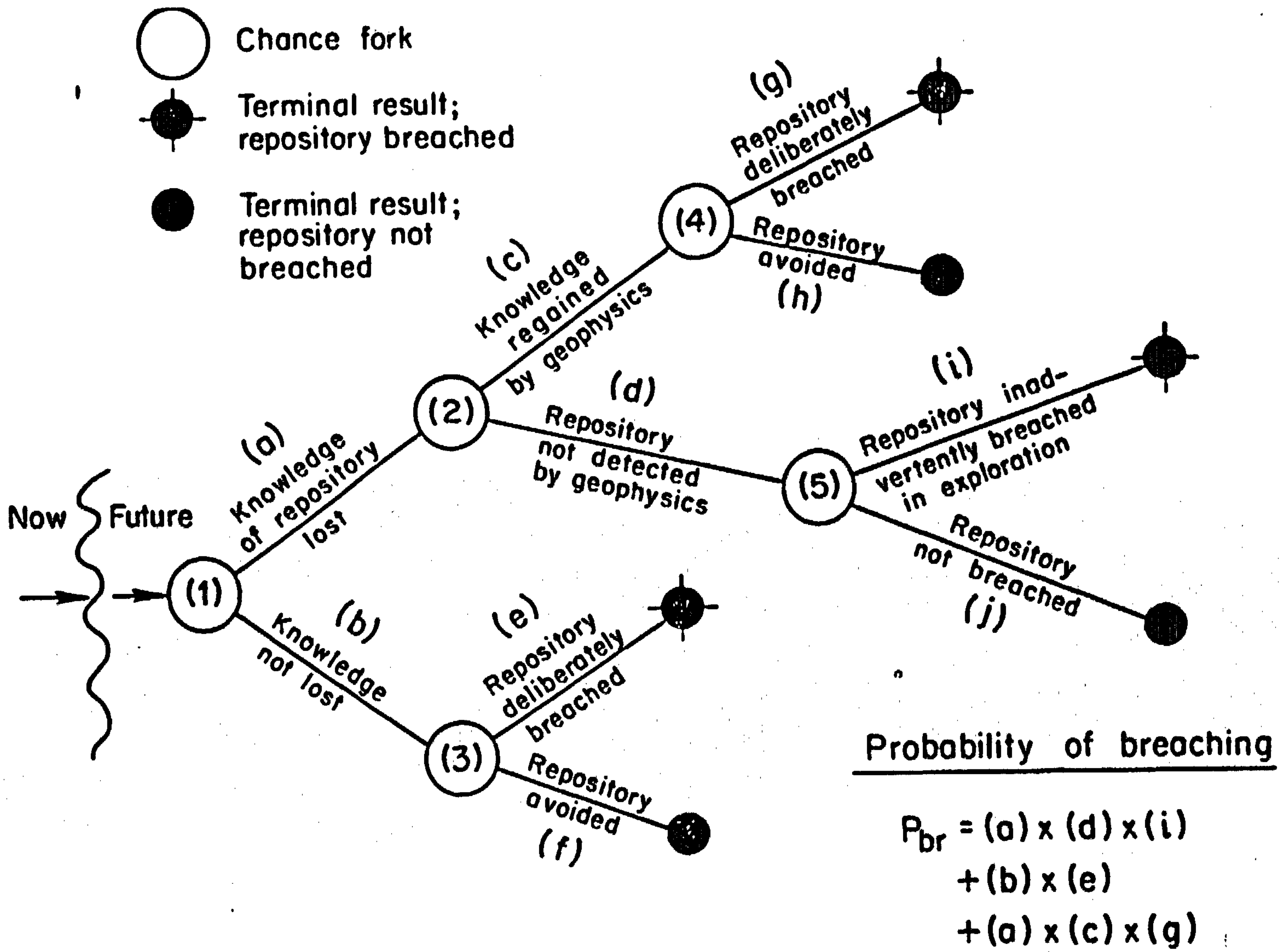


Figure 2-1. Basic probability tree involving breaching vs. not breaching a HLW repository by human activity. Numbers identify individual chance forks, and permit successive extensions of the tree (Figures 2-2, 2-6, 2-10, and 2-11) to be linked together (Figure 2-12).

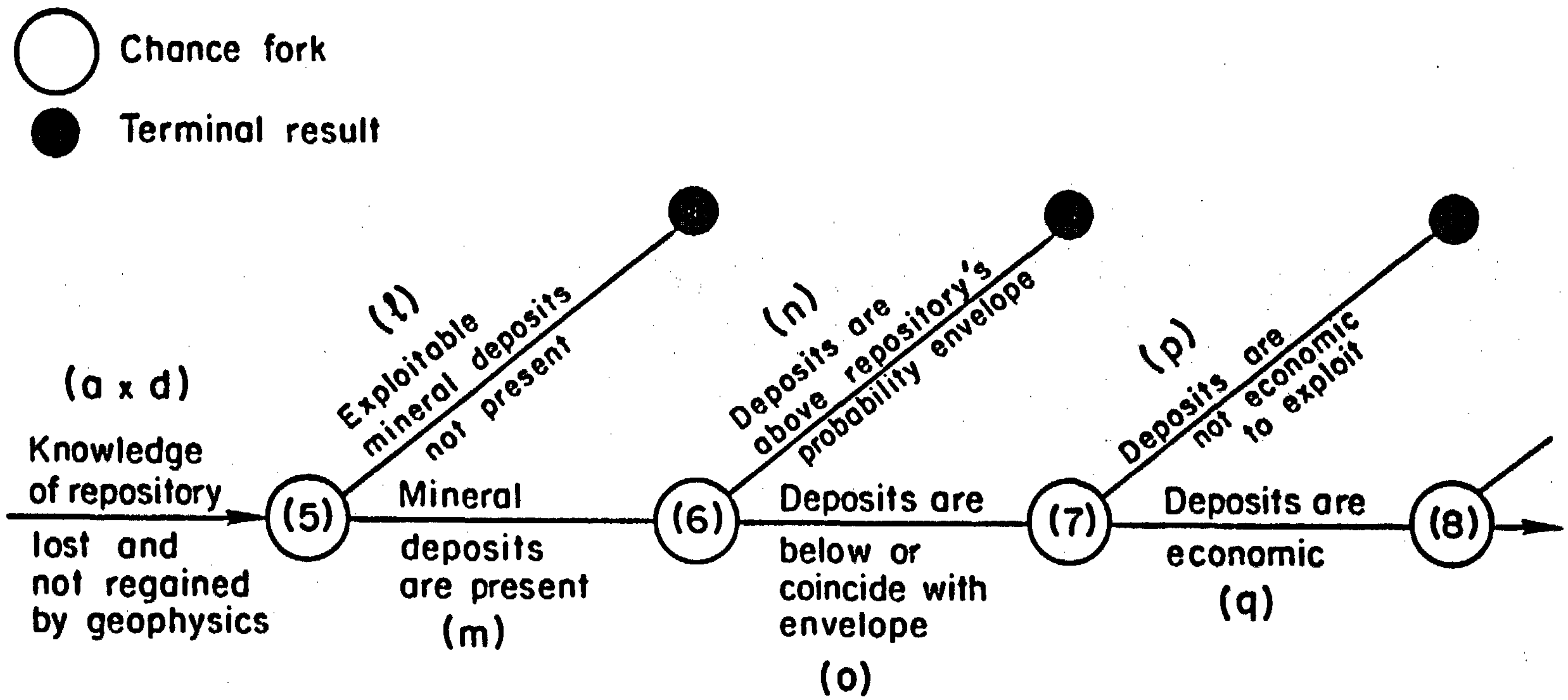


Figure 2-2. Second-stage probability tree diagram that extends branch (d) of Figure 2-1.

Now, let us focus on chance fork (5) and branches (i) and (j) of the basic tree. We can expand the tree as much as we wish. One possible expansion (Figure 2-2) possesses more detail than the previous tree (Figure 2-1), but it is still much simpler than more detailed representations that could be constructed. Except for the last chance fork on the right (Figure 2-2), the chance forks lead either to terminal events that involve "not breaching," or lead to another chance fork.

The probability tree portrayed in Figure 2-1 and its extension in Figure 2-2 is representative of the kind of analysis that is essential. The tree represents the interplay between human activity and geological endowment and requires that probabilities be supplied for each branch, if the overall probabilities attached to breaching are to be estimated.

The Repository's Probability Envelope

The three-dimensional geometry of a repository and possible locations of commodities in rocks that surround the repository bear strongly on the probability of the repository being intersected by future exploration drilling. However, we must consider not only the shape of the repository itself, but also that of a "probability envelope" that surrounds the repository. The probability envelope can be defined as the continuum of probabilities, in three-dimensional space, that radioactive waste will have migrated into the surrounding rocks. The envelope can be represented by contours drawn on planes that intersect the envelopes (Figure 2-3). Probabilities will decrease away from the repository. The rate of decrease may or may not be exponential. Probably the decrease would vary greatly with respect to direction in three-dimensional space and would be sensitive to local geologic features, including bedding surfaces, faults, igneous intrusions, and joints. The probability envelope should expand with time.

The shape and specific values of the probability envelope will be assigned by repository-site engineers, with input from experts in rock physics, hydrogeology, and geochemistry. Defining the probability envelope is essential for estimating probabilities of its inadvertent unbiased intersection by boreholes.

If the repository's probability envelope decreases exponentially with distance, zero probability will never be reached. Therefore, it will be necessary to assign some probability cutoff, beyond which the rock volume surrounding the envelope can be considered to be "safe."

The shape of the probability envelope affects the probability of its intersection by boreholes. If a vertical borehole is drilled from a surface location above the envelope, and if the borehole is sufficiently deep so that it intersects the largest probability value at that geographic location, then the probability of the borehole intersecting the envelope can be mapped by projecting the maximum probabilities within the envelope to a horizontal surface (Figure 2-3). The horizontal surface could be the land surface, and contours on it can thereby define the area that is safe versus the area that

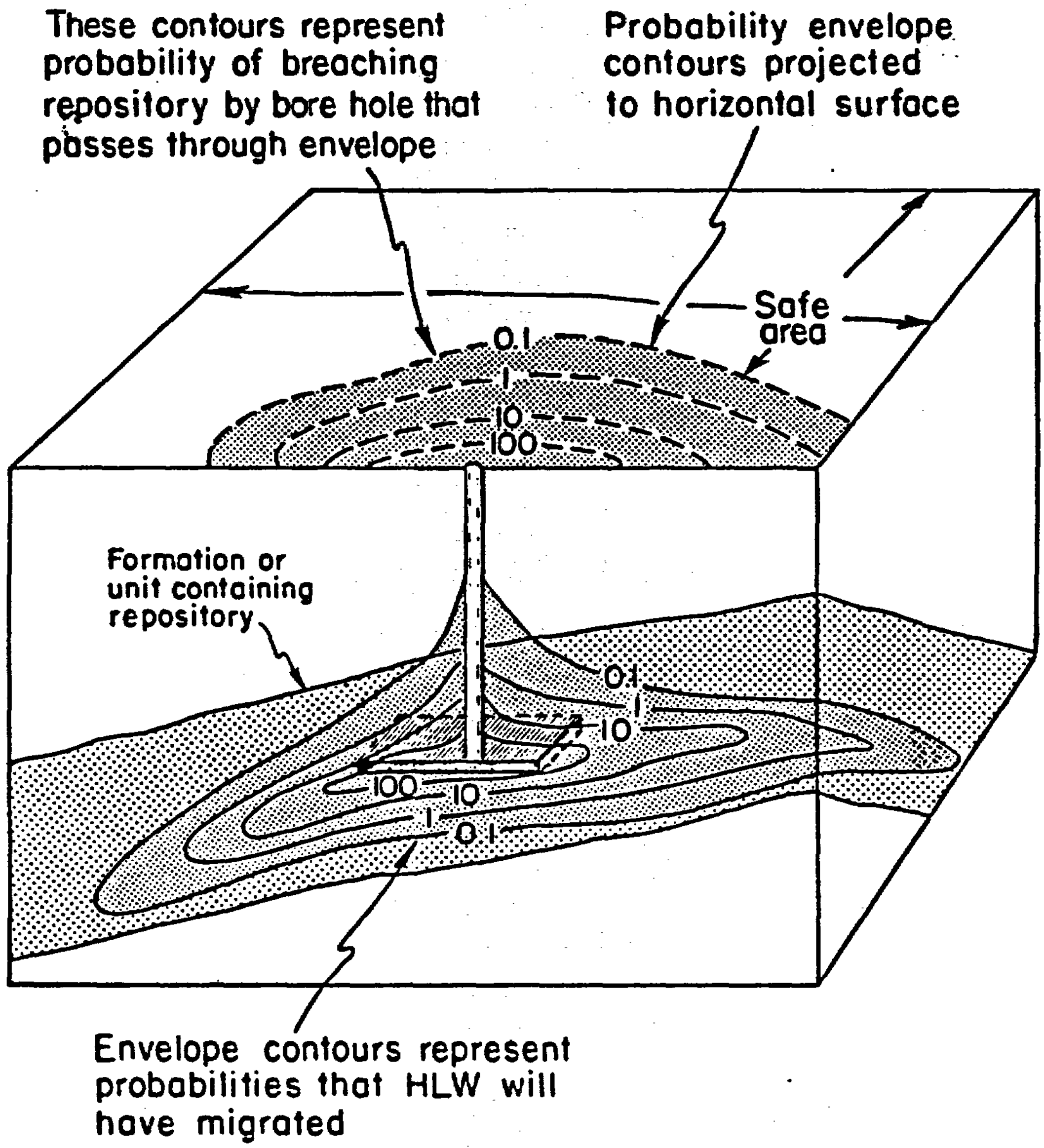


Figure 2-3. Hypothetical probability envelope surrounding repository. Maximum probability values have been projected to horizontal surface and define safe versus unsafe areas for vertical boreholes that penetrate envelope.

is unsafe. Thus, probabilities of intersection of the unsafe area vary geographically.

The depth of a borehole affects the probability of intersecting the envelope. The envelope may be thought of as consisting of a large number of layers, like a large, irregular onion that could be successively peeled, revealing progressively increasing probabilities until the core (the repository) is finally reached. Boreholes drilled to some specified depth that is less than the minimum depth of the cutoff layer of the envelope (i.e., the outermost layer of the onion), but above the repository itself, will have probabilities of intersection that are less than those drawn on the horizontal plane (Figure 2-3). These probabilities can be mapped by passing a plane representing the specified intermediate depth through the envelope (Figure 2-4). These probabilities then can be projected to the land surface, defining safe versus unsafe areas.

The probability of a borehole intersecting the envelope can be calculated readily. A borehole that is shallower than the minimum depth of the probability envelope's cutoff value forms a special case, with zero probability of intersection.

At this point, the concept of a "unit area" must be introduced. Suppose that we define a unit area as an area outlined by a square. The size is arbitrary, but it would be convenient if the size were sufficient to encompass the projection of the probability envelope, with some area to spare (Figure 2-5). If a vertical borehole is drilled in an unbiased manner within the unit area, either at random or as part of a grid, the probability of intersecting the probability envelope is given by the proportion of the unit's area occupied by each of the different levels of the probability envelope.

About two-thirds of the unit area in the hypothetical example (Figure 2-5) is in the "safe" category, that is, below the cutoff level of 0.1 percent chosen arbitrarily. For the remaining third, the proportion of the area occupied by each subenvelope (or layer of the onion) must be calculated, and the area multiplied by the respective value of the subenvelope. If values of the probability envelope decrease exponentially with distance away from the repository, a slight problem in carrying out the calculations is encountered. We cannot readily compute a mean value for such a subenvelope and multiply it by its area, and the presumed irregularity of the envelope would rule out classical integration procedures. A Monte Carlo procedure to obtain the probability would be easiest, particularly if the shape of the probability envelope is intricate. The projection of the probability envelope could be digitized by superimposing a grid of appropriate fineness over the projection and encoding the value of the envelope of each point. Then a succession of x and y coordinate values (e.g., north-south and east-west) drawn at random from a uniform distribution and the encoded probability values combine to yield the probability of intersection on a unit-area basis. A computer program to accomplish this would be only a few dozen lines long and could be easily prepared.

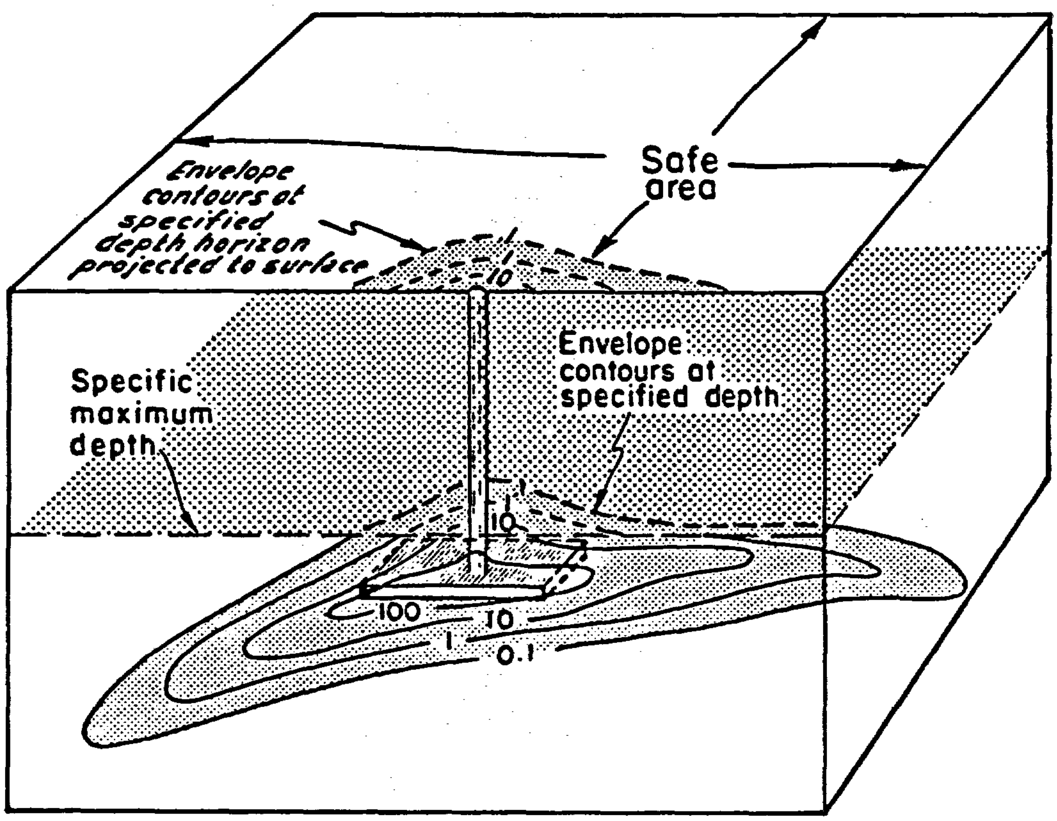
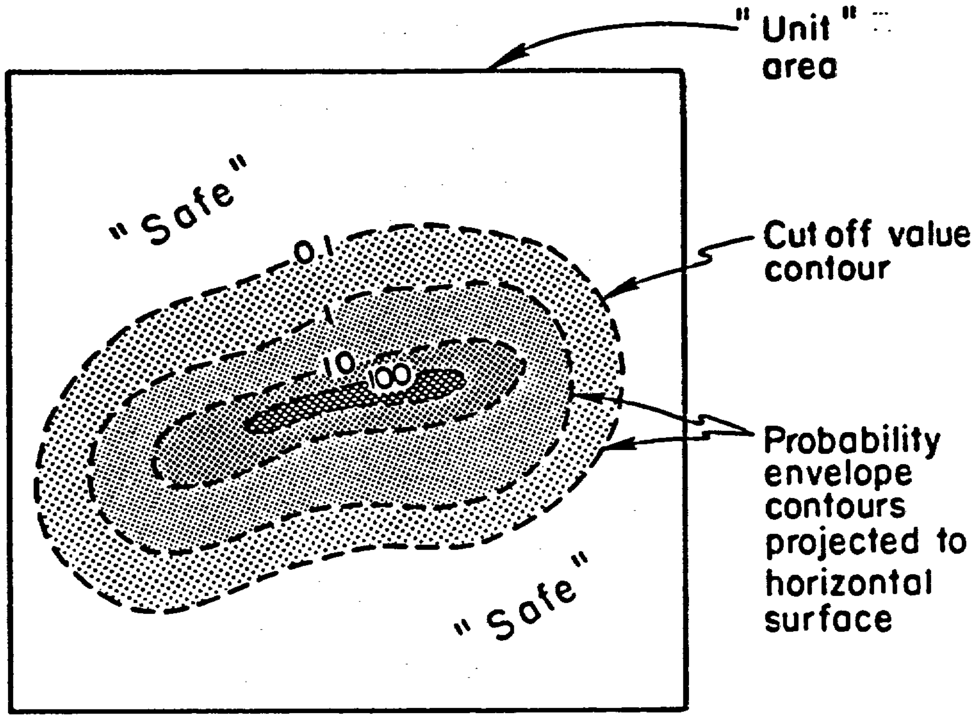


Figure 2-4. Effect of setting depth limit for borehole such that borehole penetrates only part of envelope.



Probability of intersection
within unit area

$$P = \text{number of holes} \times \frac{\sum \text{area of subenvelope} \times \text{prob. envelope value}}{\text{unit area}}$$

Figure 2-5. Unit area onto which contours of probability envelope have been projected. Random sampling, by Monte Carlo procedure, will yield probability that borehole, whose location is unbiased within unit area, will intercept probability envelope.

Consideration of Future Economics and Exploitability Versus Depth

At this point in the discussion we face the dilemma of whether to consider future economics in deciding whether a mineral resource is potentially exploitable. The classical definition of an ore deposit (or for that matter, of any mineral commodity) is that it must be economically exploitable. This definition often is used loosely. A deposit of gold may shift back and forth between an "ore" and a "non-ore" simply by virtue of variations in the price of gold.

Assessing the likelihood of potentially exploitable mineral commodities being present in repository site areas requires a definition of economic exploitability. Undiscovered deposits in repository site areas must be regarded as having some probability of being potentially economic for exploitation in the future, if future exploratory drilling is to be undertaken in search of them.

One approach is to consider future demand for a specific mineral commodity on a relative basis, conveniently on a scale of 0.0 to 1.0, so that it may be combined multiplicatively as if it were a probability estimate (Figure 2-6). If the "relative demand" is zero, then regardless of the presence of deposits of the commodity, no incentive to search for it will exist. On the other hand, if the relative demand is 1.0, multiplication involves no change in the overall probability calculations.

A hypothetical illustration (Figure 2-7) of how relative demand for specific commodities might vary with time illustrates our problem, because we cannot objectively forecast relative demand for the next century, let alone over a 10,000-year period.

An additional quasi-economic factor is the effect of depth on economic exploitability. Exploitation costs generally increase exponentially with depth, as do exploration costs. Ideally then, we should also consider depth as an economic factor, defining a relative "exploitability/depth index" on a scale of 0.0 to 1.0 (Figure 2-8). Given an exploitability/depth index estimate, we can use it as a multiplier. A value of 1.0 thus has no effect when multiplied, but lesser values cause the exploitability estimate to decrease in proportion, culminating in zero at some depth below which the commodity is not economically exploitable.

An exploitability/depth index thus combines engineering capabilities and economics of deep drilling or deep mining. We could estimate current costs of mining or of oil and gas production with depth, but can estimates that apply today be extrapolated over the next 10,000 years? Any extrapolation is fraught with peril, but failure to extrapolate may give rise to problems with regard to the definition of potentially exploitable deposits in a repository area. For example, limestone and shale suited for making Portland cement may exist beneath a repository site. Limestone and shale are not currently exploitable as raw materials for cement manufacture unless they can be quarried; their present exploitability/depth index falls to zero at depths of one or two hundred feet below the surface. But what about their exploitability/depth index in the future?

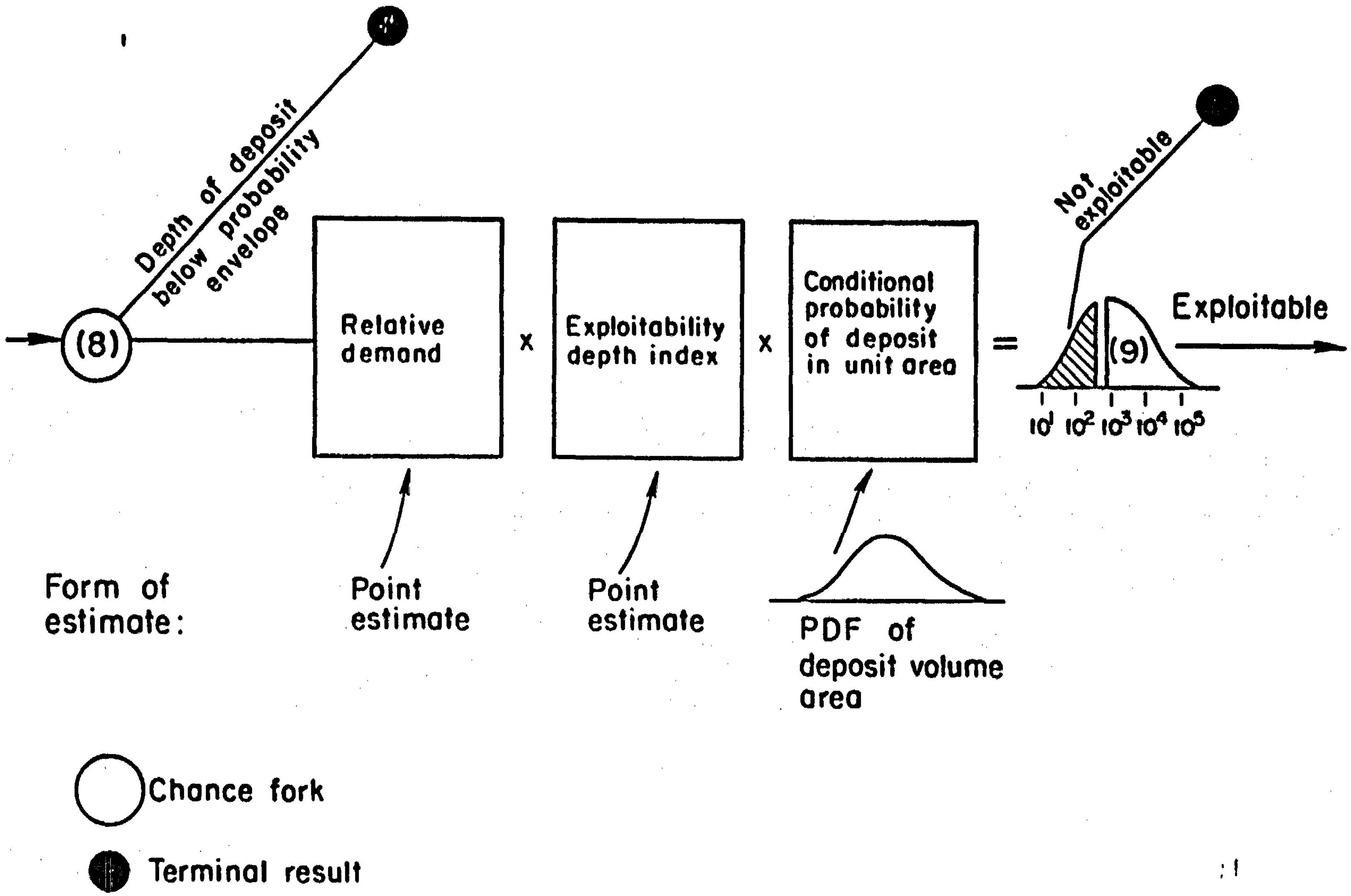


Figure 2-6. Multiplicative roles of relative demand, exploitability/depth index, and conditional probability of commodity's occurrence.

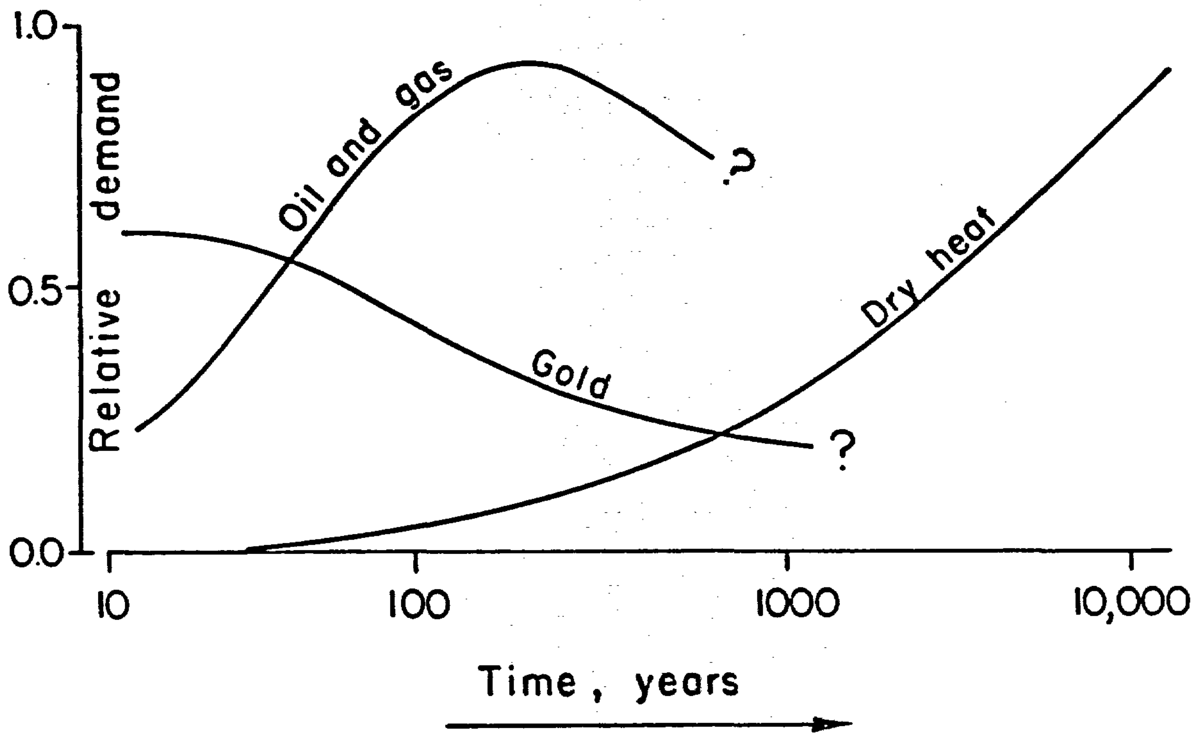


Figure 2-7. Hypothetical curves representing relative demand versus time.

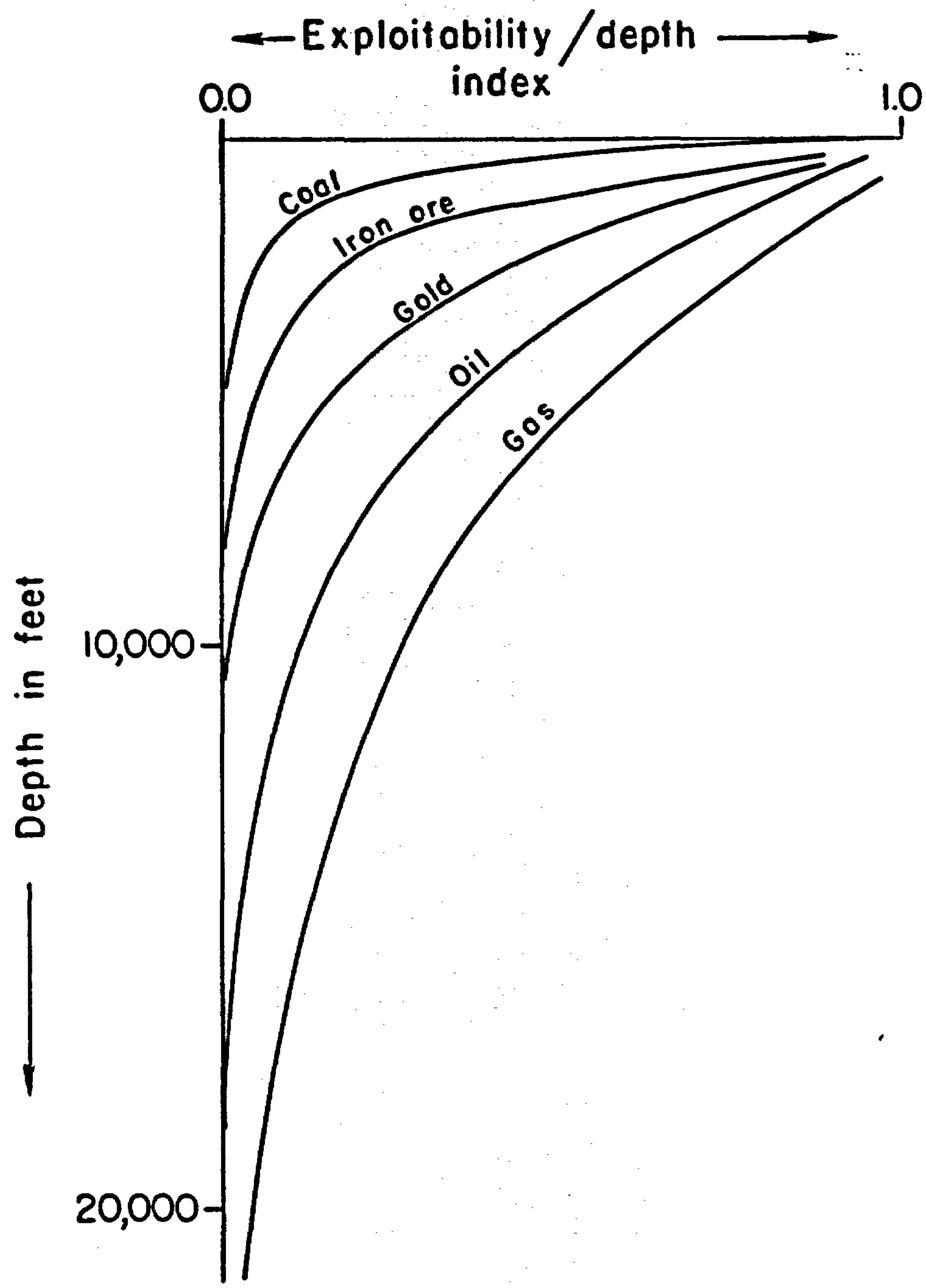


Figure 2-8. Hypothetical curves representing exploitability as a function of depth.

Conservatively setting the depth/exploitability index values to 1.0 raises the specter of the probable presence of a variety of nonmetallic deposits in any repository site area.

Widely used nonmetallic mineral commodities perhaps should be ignored, and we perhaps should focus on metallic deposits that are appreciably above background concentrations. However, consider a Carlin-type gold deposit, with finely disseminated gold in concentrations of a small fraction of an ounce per ton. Such deposits are currently economic to exploit by open pit mining at shallow depths, even though they have concentrations expressed as a multiple of the background level that are much less than in traditionally exploited gold deposits. Of course, exploitability of a Carlin-type deposit is presently extremely dependent upon depth, but what about the future?

Estimating Conditional Probabilities for Specific Mineral Commodities

Three factors govern the probability that an exploitable mineral commodity is present in a given unit area (Figure 2-6): the commodity's relative demand, its exploitability/depth index, and the conditional probability that the specific commodity (or specific aggregation of commodities) occurs within the unit area. The probability is "conditional" in that it depends upon present knowledge or inferences concerning the geology of the area.

Suppose that we know or infer that several principal groups of rocks are present beneath the repository within the unit area containing the repository site. These groups might include a Precambrian basement complex of schists and gneisses with granitic intrusions; Paleozoic marine shales, limestones, and sandstones; Mesozoic rocks; and Cenozoic volcanic flows and tuffs. On the basis of this knowledge or inference, we could assign probability density functions (pdf's) that pertain to size of deposits, conditional upon our knowledge of the geology (Figure 2-9). If we confine these pdf's to individual groups of rocks, the pdf's will reflect the influence of the rock group on our assessment of each pdf. For example, the pdf for oil and gas should be more favorable for the group consisting of Paleozoic marine rocks than pdf's for the other two groups. On the other hand, the pdf for metallic ores may be greatest in the Precambrian basement.

We can express pdf's on a unit-rock-volume basis. The rock volume can be estimated by multiplying the unit area times the average thickness of the group. Of course, we will have to assume an arbitrary depth limit for the lower boundary of the Precambrian basement complex.

If pdf's are obtainable, then a theoretical procedure for obtaining a pdf combines the conditional probability for the commodity, its relative demand, and its exploitability/depth index (Figure 2-6). The resulting cumulative pdf obtained as the product of the three pdf's could be separated into exploitable and nonexploitable components, provided that the boundary separating the two categories could be defined. Defining the boundary is an economic issue.

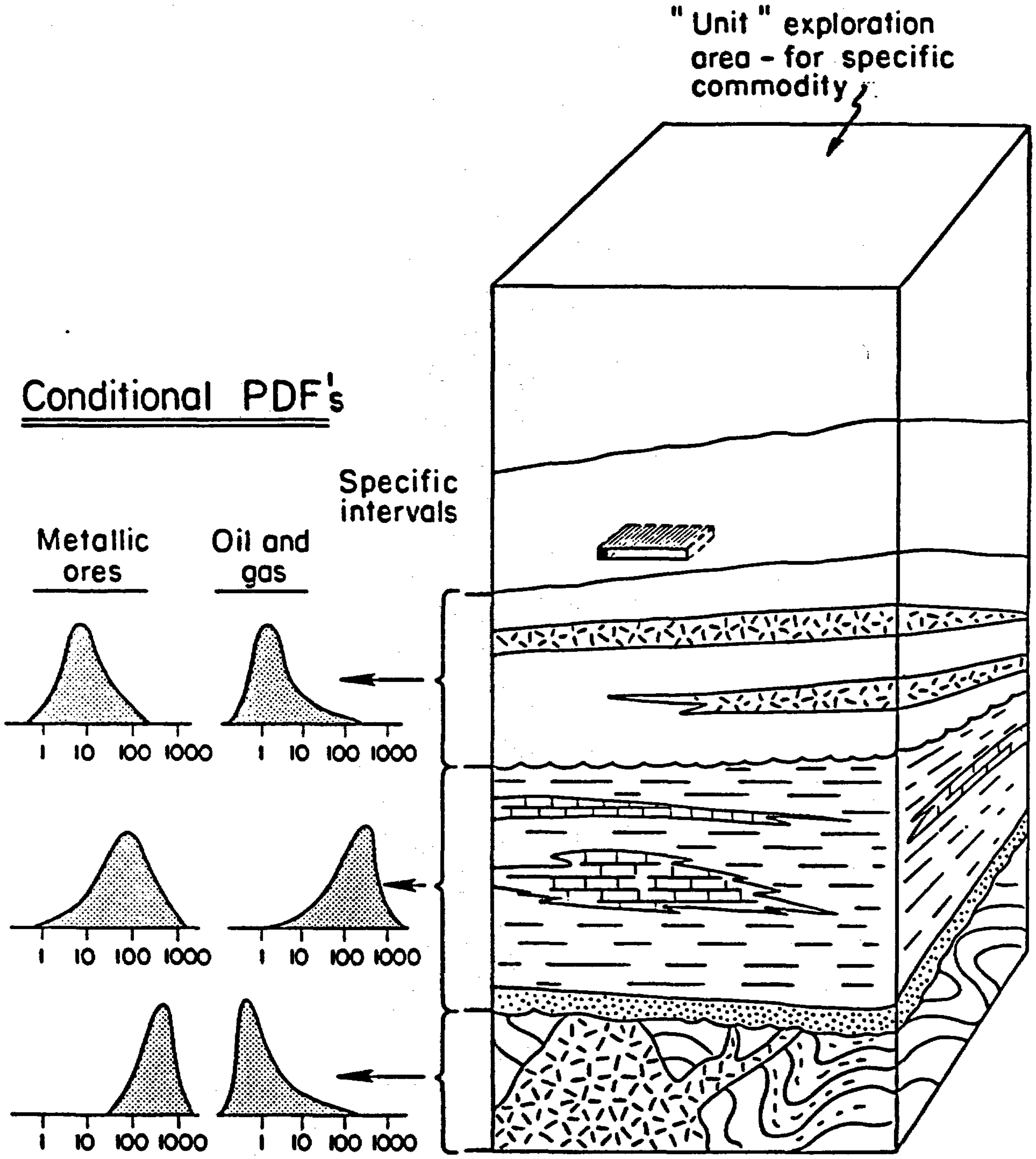


Figure 2-9. Hypothetical diagram to illustrate probability distribution functions, for aggregates of commodities, that are conditional upon specific geological groups of rocks and their volumes, within unit area.

A major question is whether conditional pdf's can be obtained more or less objectively or only as expert guesses. Before beginning, let us define desirable general specifications for estimating pdf's, as follows:

1. We need geologic analogs, preferably from within the region containing the repository, or perhaps in several regions outside the region that contains the repository.

2. Geologic analogs should involve rocks of the same general lithology, structure, and age.

3. The analogs should have been deposited under similar conditions and within equivalent tectonic settings.

4. Postdepositional (or postorigin if not sedimentary rocks) history of the analog rocks should be similar, including depth of burial.

5. The analog region should be more or less maturely explored and exploited, permitting frequency distributions of commodity volumes to be established.

6. Frequency distributions of commodity volumes should be expressible on both a per-unit-area and a per-unit-rock-volume basis.

Conditions 1 through 6 commonly are difficult to satisfy, and severe compromises often are essential if an attempt is made to use conditional pdf's. Furthermore, segregating mineral commodities to obtain pdf's for individual commodities is extremely difficult.

I shall return to these problems later. Next, however, let us consider procedures for relating pdf's, on a unit-volume or unit-area basis, to probability distributions pertaining to the number of exploratory holes needed to reasonably prove the presence or absence of an exploitable commodity or aggregate of exploitable commodities. If feasible, these procedures would lead in turn to estimates of the probability that a repository envelope will be intersected in drilling.

Estimating Probabilities for All Commodities Combined

We must estimate the probabilities for all exploitable commodities combined. This is a difficult task. If we assume that the probabilities attached to different groups of commodities are independent of each other, then we can use the binomial distribution, provided that we are content to treat each exploitable commodity category as being either present or absent. Suppose that we establish only three categories: fuels, metals, and nonmetals. We can write the binomial distribution as

$$(P_f + A_f)\ (P_m + A_m)\ (P_n + A_n)$$

where P is presence, A is absence, and f, m, and n are fuels, metals, and nonmetals, respectively. Expanding the binomial, we obtain

$$P_fP_mP_n + P_fP_mA_n + P_fA_mP_n + P_fA_mA_n + A_fP_mP_n + A_fP_mA_n + A_fA_mP_n + A_fA_mA_n \quad .$$

Of course, we can use a binomial distribution with more categories, but the principle is the same. Each term in the expanded binomial yields the probability attached to that specific combination. The probabilities of all the terms sum to 1.0.

The categories must be statistically independent, a difficult requirement to satisfy. Literature that bears on the statistical independence of given categories of mineral resource commodities is virtually nonexistent, insofar as I am aware.

We are not confined to use of discrete binomial distributions. We could use continuous pdf's that pertain to the sizes or values of deposits, provided that we can transform the various commodity units into a single unit, common to all. The only unit capable of serving in this fashion is a monetary unit, e.g., present US dollars or future US dollars. If we transform the pdf's so that they are expressed in monetary units, then they can be combined by multiplication, employing simple Monte Carlo procedures. A single pdf would then be obtained for all commodity categories. As with the binomial distribution, the presumption of independence between the various distributions that are subsequently combined is essential.

I think that it is reasonable to assume that major commodity categories are more or less independent. The prospect of transforming continuous pdf's to monetary units is challenging, but if we assess values for commodity categories in present dollars, the task is not insuperable.

Probability of Intersection of Probability Envelope in Exploratory Drilling

Calculating the probability that one or more exploratory holes (drilled per unit area) will intersect the probability envelope is simple in principle, but more complex in practice. If holes are located without bias, and if there is no minimum distance between holes, then the probability of intersection by a hole is proportional to the sum of the areas occupied by each of the various probability subenvelopes with respect to the unit area, multiplied by the probability value within each subenvelope (Figure 2-10). The issue then becomes how many exploratory holes will be drilled within the unit area. The actual situation, however, is more difficult, and we face a complex set of issues:

1. Should we assume that records will be kept by future explorationists, so that the presence of a previously drilled exploratory hole may either encourage or discourage subsequent holes being drilled in the immediate vicinity?

2. If the result of an exploratory hole is discouraging (for example, a dry hole drilled in search of oil and gas) does it "block out" a specific subarea, inhibiting subsequent drilling within the subarea to the depth drilled?

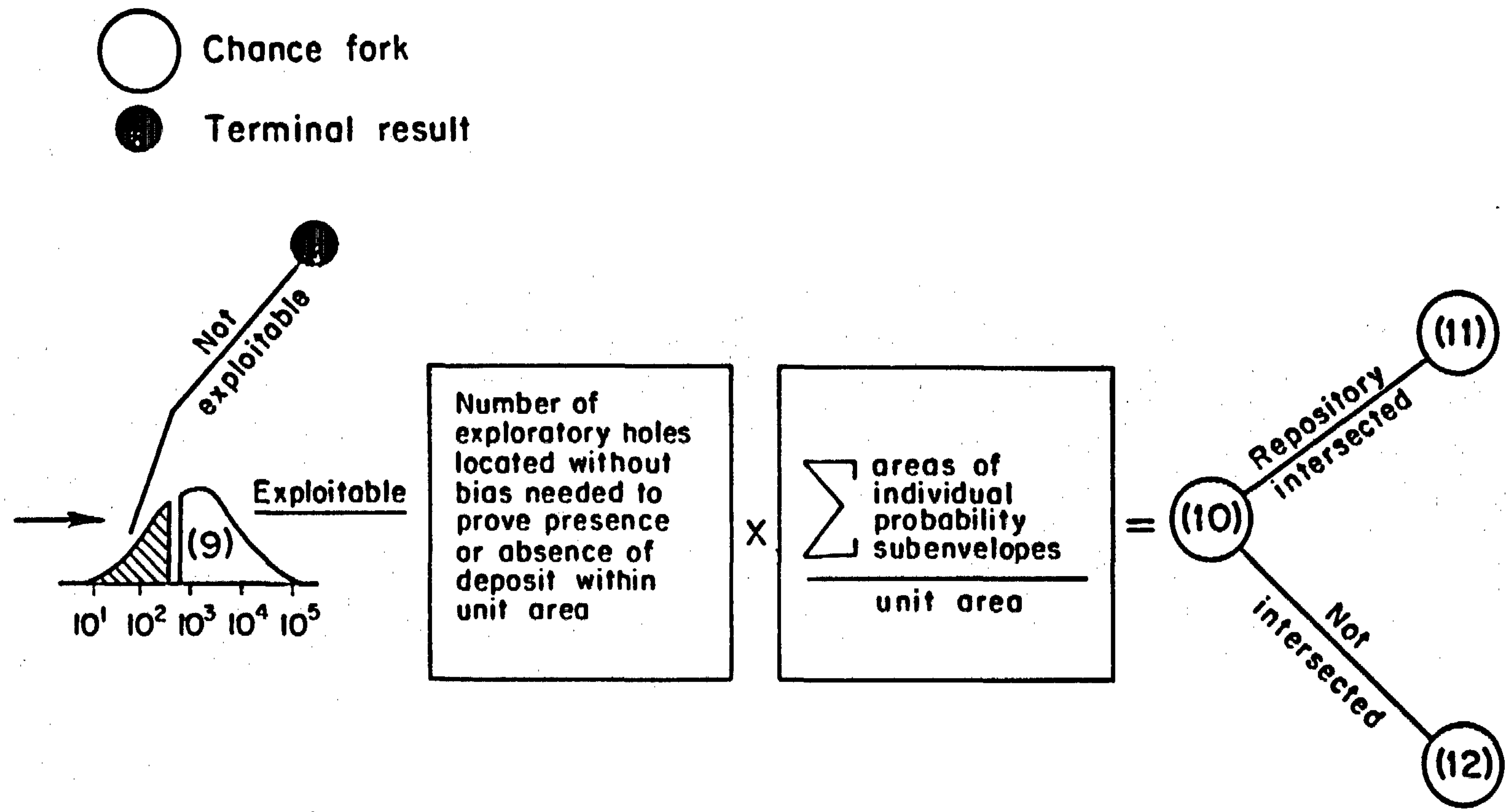


Figure 2-10. Diagram to illustrate probability of repository being intersected on unit-area basis.

3. If a subarea is more or less "blocked" from further drilling, how big is the area, and what is its shape (a circle, square, or hexagon)?

4. Will future explorationists be guided by geology, and if so will the presence of geological "leads" encountered in drilling (in contrast to direct discovery of an exploitable commodity) have major influence on decisions to drill or on location of subsequent exploratory holes?

These questions seem unanswerable. Of course, we can speculate upon them, and given a specific set of detailed assumptions we could deduce a procedure for estimating probabilities of intersection. The point is that we must have explicit guidelines for each of these issues if an event tree of sufficient complexity is to be considered (Figure 2-11).

A key issue is the necessity (if we are going to treat the whole sequence of events probabilistically) of assigning a probability of breaching (i.e., escape of part or all of the contents of a repository to the surface via a borehole). We need to assign these probabilities now, even though they may involve drilling technology that is hundreds or thousands of years in the future.

Sources for Frequency Distribution of Specific Commodities or Categories of Commodities Expressable on a Unit-Area Basis

Pdf's must be expressed on a unit-area basis if we are to estimate probabilities of intersection of a repository by a borehole. Ideally, pdf's should be on a unit-rock-volume basis, which in turn can be reexpressed on a unit-area basis. Ideally, sources for pdf estimates should consist of frequency distributions of individual commodities. Sources for data are past production of some individual commodities; production statistics, in turn, can be manipulated to yield projections of the resource base with respect to specific commodities.

Oil and Gas

Most states in the United States compile production statistics for oil and gas on a field-by-field basis. For example, the Kansas Geological Survey publishes an annual report on oil and gas produced in Kansas, with statistics on the amount produced during the year and cumulative totals for each field. From this information, frequency distributions of field size based on cumulative production are readily tabulated. It is generally convenient to plot these frequency distributions in log-probability form, because distributions of cumulative production figures are more or less lognormally distributed (i.e., if we plot logarithms of field volumes, they approximate a normal or Gaussian distribution). If plotted in log-probability form, an ideal lognormal distribution is a straight line, which is convenient (but hazardous) for making projections for large fields with small probabilities.

The US Department of Energy (DOE) has prepared estimates (unpublished) of ultimately recoverable oil and gas on a field-by-field basis. These estimates

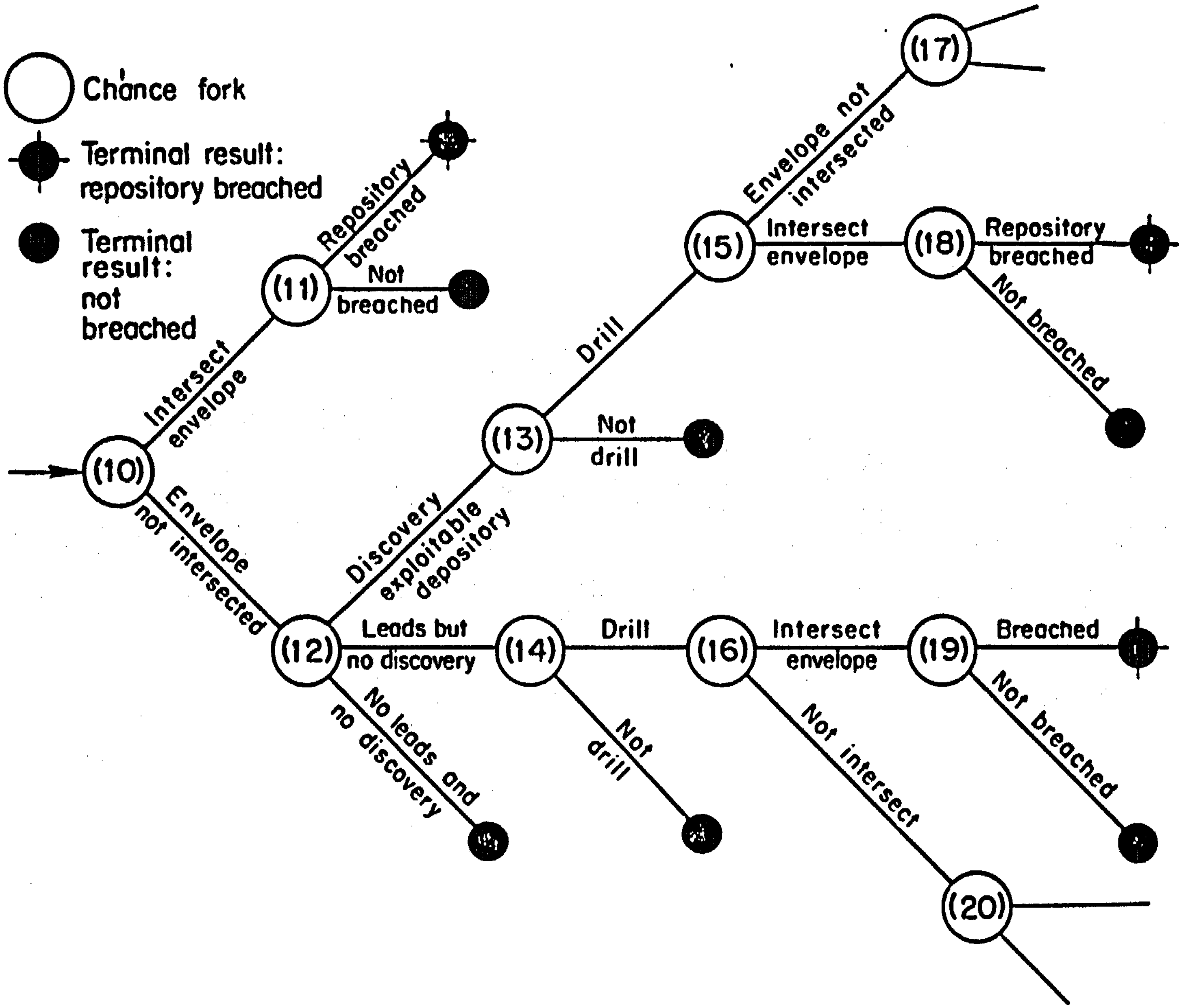


Figure 2-11. Expanded tree dealing with events subsequent to drilling of boreholes in area of repository site.

extrapolate decline rates to yield estimates of ultimate recovery per field. This is a "quick-and-dirty" method at best, but it yields numerical estimates, however imprecise. Other groups have produced estimates of ultimate recovery employing decline rates plus other engineering considerations (e.g., Barlow and Haun Inc., 1978, for Wyoming).

If we are concerned with ultimately recoverable oil and gas in a region in terms of the region's resource base, we can take production data from a relatively mature area, extrapolate decline rates of existing fields to obtain their ultimately recoverable hydrocarbons, and also extrapolate progressive changes in field-size distribution to the oil and gas obtainable from as-yet-undiscovered fields (Harbaugh and Ducastaing, 1981). Such a procedure is useful for estimating the resource base in regions that have been more or less extensively explored. Bloomfield and others (1979) presented statistics on the relationship between oil field sizes and sequence of discovery.

If the area for which a resource base is estimated is circumscribed, we can divide the regional estimate by the area of the region to put the estimate on a unit-area basis. We can also put the estimate on a unit-volume basis by incorporating the thickness of the interval that has been explored. One problem, however, is that it is rare to find an area that has been explored uniformly with respect to depth. Intensity of exploration generally decreases downward, because there are more shallow holes than deep holes.

There are no great technical problems in obtaining unit-area and unit-volume estimates of recoverable hydrocarbons in much of the US. The real problem is in deciding which areas in the US (or, for that matter, the world) provide appropriate analogs for specific proposed HLW repository sites. Consider the Nevada Test Site (NTS). There is some finite probability that marine Paleozoic rocks, including limestone and shale, are present beneath Yucca Mountain. If marine Paleozoic rocks are present beneath Yucca Mountain, do analogs in other regions that have been explored permit unit-area or unit-volume estimates of the Yucca Mountain area's hydrocarbon potential to be made? Appropriate analogs for Paleozoic rocks that may be present at Yucca Mountain are difficult to suggest. Many regions of marine Paleozoic rocks in the United States are known to yield oil and gas, but none, to my knowledge, provide good analogs for the Yucca Mountain area.

Metals

Estimates of ore deposits in the vicinity of a repository site are also needed. The procedures are basically the same in principle as for oil and gas, namely, to find a region or regions that are more or less analogous geologically and have been substantially explored. Here we have enormous difficulties. Regions that have been explored for ore deposits with the same intensity as certain regions that produce oil and gas are almost impossible to find. For example, in central Kansas, counties such as Russell and Barton Counties have been thoroughly explored for oil and gas; most of the veneer of Paleozoic sedimentary rocks that overlie the Precambrian basement has been thoroughly sampled by drilling. Although some small oil and gas fields probably are left to be found in these counties, we can readily estimate the contribution of these remaining undiscovered fields to the total petroleum resource base.

No region that has been explored to a comparable extent for metals is known. Areas may have been relatively thoroughly explored for ore deposits close to the surface (that is, within a few hundred feet or less of the surface), in some mining districts, such as in the Butte district or in the Southeast Missouri lead district, locally there has been relatively intense exploration to depths that are substantially below the surface.

Setting aside the problem of exploration intensity, do regions exist that could provide analogs for ore deposits in groups of rocks inferred to be present beneath repository sites? Again, consider Yucca Mountain at the NTS. If marine Paleozoic limestones and shales are present, what analogs are appropriate? Should Mississippi Valley lead and zinc deposits be considered, or those of the Leadville, Colorado, carbonate district? If a basement of high-grade metamorphic rocks that has been extensively intruded is present beneath Yucca Mountain, do areas of Colorado in which more or less comparable Precambrian rocks crop out provide analogs? The Canadian shield also may provide suitable analogs. Selecting appropriate analogs for nonmetallic deposits (excluding fuels) is even more challenging.

The Unit-Regional Value Approach

An alternative to the above procedures is simply to lump all mineral commodities together according to their monetary value (expressed in constant dollars) and to measure monetary value for the crust as a whole, treating it on a unit-area basis. This is the "unit-regional-value" (URV) approach championed by Professor John C. Griffiths of Pennsylvania State University. Griffiths and his students have produced an extensive series of published papers, theses, and unpublished reports, cited below. The URV procedure has the advantage of reducing or avoiding difficult assumptions regarding geologic analogs and difficulties of dealing with different mineral commodities.

Whereas the URV approach is a measure of human activity, it also provides some measure of the endowment of Earth's crust with exploitable mineral commodities. The records available for URV computations go back only a century and a half or so, at best, and usually not that far. Mankind has used mineral resources for many millenia; the value of commodities produced over the centuries, if transformed to monetary units, would be immense, albeit incalculable. In spite of its shortcomings, a URV procedure may be suitable for assessing the resource potential of proposed repository areas, although it too poses major problems.

Griffiths (1978) provided an excellent generalized overview of mineral resource assessment using the unit-regional-value concept. He summarized the URV for each state in the US, for aggregate production from 1905 through 1972. The URV for the 50 individual states forms a lognormal distribution, inasmuch as URVs, expressed as dollars of mineral production per square kilometer, provide a reasonable approximation to a normal distribution when their logarithms are plotted. To compensate for changes in the value of the US dollar from 1905 through 1972, the 1967 dollar was chosen as the standard. The quantity of a specific commodity that a dollar would buy in 1967 was used to transform the production figures for all years into 1967 dollars.

Griffiths showed that the unit regional values of the 50 states vary enormously, ranging from a maximum of $810,179/km^2 for Pennsylvania, to a minimum of $2,739/km^2 for Alaska (the figure for Alaska is now greater by virtue of oil production from Prudhoe Bay). The value for the 50 states of the US as a whole, for the 1905-1962 period, was $98,345/km^2, and $117,023/km^2 for the 48 conterminous states.

These figures are not directly conditional upon geology. Furthermore, they span only a short segment of human history, about two-thirds of a century, whereas our purview in this present report is the next 10,000 years, or about 133 times as long! What URV figures do tell us is that there is major diversity in the extent to which mineral resources have been exploited to date. An important question is whether these differences from state to state also reflect differences in mineral endowment. Both endowment and exploitation activity are important. For example, Alaska's small URV (even including Prudhoe Bay field), reflects a relatively low level of exploration effort per unit of area, and therefore Alaska's potential on a URV basis may be much larger than past production figures might suggest.

A major point of the URV approach is that all categories of mineral resources are lumped together. Contrast the first four states in the US in terms of their URVs for 1905-1972. Pennsylvania and West Virginia are first and second, respectively, and coal and petroleum have been their predominant commodities. Louisiana is third (principally petroleum), and New Jersey is fourth (principally sand and gravel). South Africa's overall URV (Menzie, 1977) lies close to that of the US as a whole. In the US, petroleum is the largest single commodity, with fuels overall accounting for two-thirds of the URV. In South Africa, however, gold, diamonds, and coal are first, second, and third in importance, respectively.

Griffiths and his students have surveyed a number of other countries to determine their URVs, including Canada (Labovitz, 1978), New Zealand (Watson, 1977), Australia (Engelder, 1979), United Kingdom and Ireland (Walsh, 1979), Israel (Gill and Griffiths, 1984), and Venezuela (Arteaga, 1978). Singer (1971) has treated California on a county-by-county basis.

I expressed the desirability of obtaining pdf's that are conditional upon local geology above. URV estimates can be adjusted to be conditional upon local geology. Griffiths and his students have developed a procedure to do this (Griffiths, 1978) that involves "point counting" of geologic maps. A transparent grid is laid over a geologic map, and the frequency with which specific map units occur beneath individual grid intersections is counted. Because of the diversity of map types, the map units are transformed into 14 major rock types and five major units of geologic age. The rock types are quartzite, arkose, low-rank graywacke, high-rank graywacke, carbonates, evaporites, acid intrusives, acid extrusives, mafic intrusives, mafic extrusives, ultramafic intrusives, ultramafic extrusives, and regional metamorphics. The age units are Cenozoic, Mesozoic, Paleozoic, Proterozoic, and Archeozoic. There is also an "other rocks" category, so in all there are 14 rock types and five ages, yielding a 5 by 14 classification matrix containing 70 time-petrographic units.

The number of entries in the matrix when a geologic map of a region is tabulated is a measure of its geologic diversity, and an "index of geological diversity," or IGD, ranging from 0.0 to 1.0, can be calculated (Griffiths, 1978). There is a marked relationship between geologic diversity in a region and the number of mineral commodities produced in the region. Griffiths and others (1980) plotted geologic diversity (expressed as the number of time-petrographic units present) versus the number of mineral commodities. A pronounced linear relationship is evident, although considerable scatter is present. The plot included states in the US, states in South Africa, Rhodesia, and New Zealand. Given, then, a measure of a region's geologic diversity, a conditional estimate of the number of mineral commodities expected to be present may be obtained.

How Much Exploratory Drilling Should be Expected?

The penultimate question is, how much exploratory drilling should we expect per unit area at proposed repository sites in the forthcoming 10,000 years? The answer cannot be provided unless we make assumptions about both relative demand and depth/exploitability index. If we elect to aggregate commodities in the form of unit-area-value or unit-volume-value, then the problem is to determine what specific area a vertical borehole is capable of testing to establish whether the volume that underlies a specific area is or is not exploitable.

At this point we face a formidable, if not impossible, task. At present, neither borehole geophysics technology, nor geology per se, can establish a minimum "area-of-influence" that has been explored. If we could do so, then we could calculate the number of boreholes required to test exhaustively a unit area or volume. If we make assumptions about sizes and shapes of deposits in plan view, and if we assume that when a deposit is intersected by an exploratory hole, it will be detected without fail, then we can calculate an "area of influence" for boreholes. Singer and Drew (1976) described the method for such calculations, employing simple geometrical assumptions.

Deposits of some commodities can be approximated by simple geometrical forms in plan view. For example, oil and gas fields are characterized by definite, measureable areal expanse, as are large ore deposits such as porphyry copper deposits. Seams of coal and beds of evaporites also have appreciable areal expanse. Some other deposits, however, have small areal expanse, such as steeply dipping gold-bearing quartz veins, and defy approximation by simple geometric forms.

It might be possible to gather measurements of areal dimensions of different deposits and to develop statistical descriptions of the areal expanses of the commodities used in preparing URV estimates, but the task would be formidable and perhaps impossible.

Summing Up the Literature: Are Procedures and Data Available for the Task?

In focusing on the ultimate question of whether available procedures and data permit the probability of breaching of a repository site by exploration activities to be calculated, we must focus on the literature and determine what is relevant. References are listed below that have sufficient relevance to be considered.

Data Bases Pertaining to Mineral Commodities

Most available data bases pertain either to production of mineral commodities or are relevant to exploration for them. Few data bear directly upon sizes of deposits of various mineral commodities.

Various forms of data can be used to estimate undiscovered resources. The Accelerated National Oil and Gas Resource Evaluation (ANOGRE) system of the US Geological Survey (Meyer, 1977) estimates volumes of undrilled sedimentary rock that could contain hydrocarbons and multiplies by a factor derived from other areas representing the ratio of known recoverable hydrocarbons to volume of rocks that have been drilled. The concept is simple, but the practice is complicated because subjective judgments must be made to estimate rock volume and suitability of rocks as potential hosts for oil and gas. Thus, given an estimate of the volume of sedimentary rocks and their characteristics, a point estimate of hydrocarbon volume could be generated for rocks in the vicinity of a repository site. Presumably persons in oil and gas resources assessment within the US Geological Survey could supply conversion factors that relate rock volume to hydrocarbon volumes.

Many papers discuss the attributes of data files that bear on mineral resource assessment. Meyer (1977) thoroughly reviewed petroleum resource assessment in the US. Eckstand (1977) described computer files used by the Geological Survey of Canada for metals resource appraisal. Bonham-Carter and Chung (1983) described a comprehensive procedure for integration of geologic data in uranium resource assessment, in which geologic map data, geochemical prospecting data, and airborne radiometric data were used in a study area in Manitoba, but the procedures could be used for other commodities. Chung (1983) described the computerized data-handling and analysis system used by the Geological Survey of Canada. Labovitz and others (1977) presented a computer program to standardize mineral commodity data.

A large variety of available geological, geochemical, and geophysical data have only indirect relevance to our quest here. Seismic surveys may be purchased from geophysical contractors; petroleum production data for individual wells can be purchased from Dwights; scout-ticket data for individual oil and gas wells containing stratigraphic "tops," drill-stem test data, and so forth, can be purchased from Petroleum Information ("PI"); and a large quantity of geochemical exploration data (ground-water and stream sediment) resulting from the National Uranium Resource Evaluation (NURE) Program can be obtained from the DOE (albeit in a form difficult to access). Geological surveys of most states, as well as the US Geological Survey, maintain geologic records, files, and subsurface well data of various forms that may be obtained at minimal or no cost. Data from these sources probably will not be of great value in attempting to estimate occurrence probabilities of mineral commodities at specific repository sites, because these data have little direct bearing on deposit size, grade, or geologic occurrence.

John C. Griffiths (pers. comm.) has assembled a large data base for estimating unit regional values. His data base includes digitized (and transformed) geologic map data that may be used to provide conditioned estimates of URV.

Procedures for Estimating Probabilities of Intersecting Deposits by Boreholes

There is an extensive literature of procedures for estimating probabilities associated with patterns of boreholes and for estimating measures of resource exhaustion related to density of drilling. Grid drilling procedures (which assume unfailing detection if a borehole intersects a target) use simple geometrical probability concepts. Singer and Wickman (1969) have produced sets of probability tables that pertain to elliptical targets "located" with square, rectangular, and hexagonal point nets. Singer (1975) discussed the relative efficiency of square and triangular grids. Shurygin (1976a, 1976b) and Davis (1976) have discussed relative efficiencies of various rectangular grids. Drew (1979) thoroughly discussed pattern drilling and procedures for Bayesian revision at successive stages in a multi-stage drilling program. Omre (1983) discussed procedures for combining subjective prior information with Bayesian revision dependent on results in grid drilling.

If realistic assumptions can be made about the area that an individual borehole "exhausts" with respect to a mineral resource commodity, then the extent of exhaustion, with contours of probabilities, can be mapped. Drew and others (1979) prepared petroleum exhaustion maps for the Denver Basin, using different assumptions as to target (i.e., oil field) sizes and shapes. Collins (1985) has dealt with relationships between drilling density and petroleum discovery rates through time in Kansas. Schuenemeyer, Bawiec, and Drew (1980) and Schuenemeyer, Drew, and Bawiec (1980) dealt with statistical procedures to forecast petroleum discovery rates on a regional basis.

Available procedures for calculating borehole intersection probabilities use simple shapes, such as circles and ellipses. If we were confident of the shape and size (in plan view) of deposits that might occur in a repository site area, then procedures to calculate the intersection probabilities could be developed. But, there is little incentive to extend present procedures without first defining shapes and sizes of deposits that might be present. For example, Singer's (1976) FORTRAN program for calculating intersection probabilities could be extended to use target shapes other than circles and ellipses. Deffeyes and others (1982) dealt with some of the problems concerned with other shapes and their packing.

Procedures for Assessing Undiscovered Resources

Many articles deal with resource assessment procedures. White and Gehman (1979) provided an excellent overview of methods in use for petroleum resource assessment. The general categories of methods include geologic analogy, Delphi, areal yield, volumetric yield, geochemical materials balance, numbers of oil fields and sizes in a region, Monte Carlo summation of plays and prospects, and extrapolation of discovery rates. Meyer (1978) described volumetric methods employed by the US Geological Survey.

A number of papers deal with statistical estimation procedures for oil-field sizes, for example, maximum-likelihood estimation procedures for the size distribution of North Sea oil fields of Smith and Ward (1981), or the discovery-process models of Schuenemeyer, Drew, and Bawiec (1980).

Historical data can be used to predict changes in sizes of metallic deposits according to discovery sequence, log-log grade/tonnage plots providing a relatively simple means for projection. An article by Cargill and others (1980) dealing with mercury is an example.

Procedures for estimating conditional probabilities on an areal basis have been developed. Probabilities are conditional upon one or more geologic variables that can be mapped continuously. Harbaugh and others (1977) described an application based on the properties of subsurface structure-contour maps to generate conditional probabilities of oil occurrence. Davis and Harbaugh (1983) used a regression procedure to generate pdf's of oil and gas field sizes conditional upon area of structural closure mapped seismically in part of the Louisiana and Texas outer continental shelf. Berlanga and Harbaugh (1981) devised procedures for mapping oil-exploration outcome probabilities conditional upon seismic structure maps, with an example application in the Tabasco Basin, Mexico. Agterberg (1974) described a procedure for mapping occurrence probabilities for metallic deposits, conditional upon proportions of different rock types mapped in part of the Canadian shield. Chung and Agterberg (1980) dealt with regression procedures for estimating mineral commodity occurrences from geologic map data.

Many statistical procedures for estimating undiscovered oil and gas resources deal with field-size statistics, for example, those of Lee and Wang (1983, 1985), Kaufman and Wang (1980), Meisner and Demirmen (1980), Drew and others (1980), Root and Schuenemeyer (1980), and Harbaugh and Ducastaing (1981). Although procedures in these papers vary widely, they all require an historical base of previously discovered fields. Furthermore, these procedures are not conditional upon geology, except in the sense that they can be focused on specific regions, including geologic basins.

One of the most thorough regional, statistical studies of mineral-resource potential is that of Lambie and others (1983). This study pertains to the whole of the California Desert Region, which spans southeast California and extreme east-central California, and makes use of virtually all geological, geophysical, and geochemical data that are available on a regional basis. The data include digitized geologic map units (taken by superimposing a transparent grid over maps of the California Division of Mines and Geology 1:250,000 scale geologic quadrangle map series), faults as mapped, regional gravity measurements, lineaments observed on Landsat and Skylab imagery, NURE geochemical prospecting data, NURE airborne gamma ray surveys, and mineral commodity data, consisting of both production statistics and information on occurrence when only individual locations have been reported.

The mineral-occurrence data came from a variety of sources, including (1) DOE's locations of uranium claims (maintained at DOE's office in Reno, in open-file status with the general designation Preliminary Reconnaissance Reports for Uranium); (2) mineral resources reports prepared by the California Division of Mines and Geology, for example, that by Saul and others (1971) for Riverside County; (3) locations of mines and mineral occurrences prepared by the Southern Pacific Company (1964); (4) locations of mines and occurrences in the Bureau of Mines Mineral Industry Location System, known as "MILS" (US Bureau of Mines, 1977); and (5) compilation by the US Bureau of Land Management (1979) of mines and prospects. In all, these data bases provided much of the mineral-occurrence information relevant to the region. Other data sources are listed in Lambie and others (1983) in many references to published and unpublished reports.

The data described above were used to produce four different contour maps of the California Desert area that show the probability of occurrence of four specific groups of metallic deposits, namely: (1) gold only, (2) iron only, (3) copper, lead, silver, and zinc combined, and (4) all of these metals combined. Mapping was carried out using geographic cells 2 km by 2 km in extent, each cell receiving values that express the probability that it has been correctly classified within each of these four groups. These probability values were contoured. As explained below, the probability estimates pertain only to occurrence of deposits (e.g., presence or absence) and do not pertain to sizes or frequencies of deposits.

The statistical technique used for calculating the probability of correct classification is a widely used procedure called discriminant function analysis (DFA). The particular computer program used in the California Desert Region study was described by Nie (1975). Abry (1975) also used DFA to produce contour maps of probabilities of occurrences of undiscovered oil fields in specific size categories in the Tatum Basin of New Mexico, which is part of the much larger Permian Basin.

Results of the California Desert study, although expressed as numerical probabilities, are qualitative. A specific geographic cell can be classed as prospective for the occurrence of various metals as defined for each of four groups, but no measure of the magnitude of deposits that may be present is given. Note that the probability of correct classification in each of the four groups is conditional upon available geologic information. Thus, there is strong similarity to the general objectives of Griffiths (1978) in attempting to establish relationships by which regional geology may be used to enhance prediction of resource occurrences. Griffiths (1978) and his students (e.g., Labovitz and Griffiths, 1982) have worked principally with information extracted from geologic maps, whereas the California Desert Region study of

Lambie and others (1983) employed other forms of geologic data (including geophysical and geochemical data), in addition to geologic map data.

Conclusions

Analysis using probability trees makes clear that probabilities of breaching of a HLW repository by exploratory drilling are interdependent with probabilities pertaining to future human behavior and history. The probabilities of breaching by drilling cannot be calculated in isolation from these influences. Figure 2-12 represents an overall probability tree, combining the elements shown in Figures 2-1, 2-2, 2-6, and 2-11.

We cannot produce objective estimates of mineral resource potential on a unit-area or unit-rock-volume basis, if a variety of mineral commodities are to be considered. These estimates cannot be prepared for the near future, much less for the next 10,000 years. The only widely available resource data that allow a reasonable estimate on a rock-volume basis pertain to oil and gas fields in some regions that have been maturely explored. Available data pertaining to mineral production of commodities, including metals, stone, brines, and sand and gravel, are difficult to translate to a total resource inventory on a unit-area basis, and their translation to a unit-rock-volume basis invokes assumptions concerning depth versus exploitability that are extremely difficult.

The future economics of mineral resource exploration cannot be objectively treated and yet cannot be ignored. If depth is ignored as an economic factor, then we face the problem of the possible presence of mineral deposits at substantial depths, for which equivalent deposits may be currently exploitable near the surface but are decidedly uneconomic at depths greater than one or two hundred feet today. Thus, probability estimates of future economic factors must be largely subjective.

Areal shapes and sizes of some deposits are only poorly known, and existing information does not permit a statistical inventory to be made. Areal shape and size statistics are essential if intersection probabilities by boreholes are to be calculated accurately. Information on areal shapes and sizes of oil fields is more or less available, but detailed statistical studies of shapes of oil fields have not been made. Procedures for estimating intersection probabilities for point nets (e.g., grid drilling) are available only for targets defined by circles or ellipses, but procedures for other shapes could be developed.

If a "probability envelope" can be established for a repository site, calculating probabilities of intersection by vertical boreholes of prescribed depths is readily handled by Monte Carlo procedures. The probability of intersection by slanted boreholes could also be calculated.

There is no present method by which the area of exhaustion (or more properly, rock-volume of exhaustion) of a borehole can be determined for most

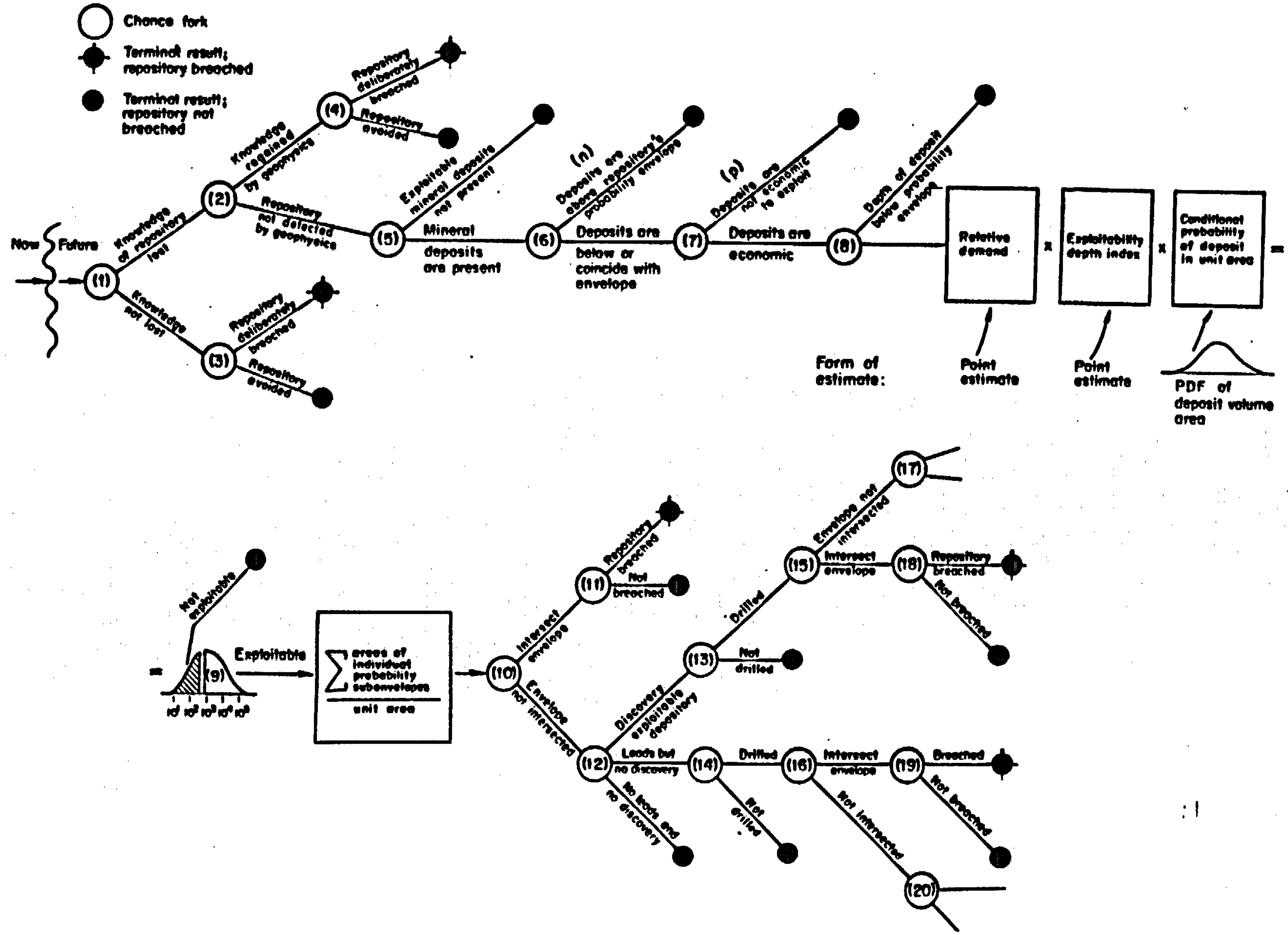


Figure 2-12. Overall tree combining elements shown in Figure 2-1, 2-2, 2-6, and 2-11.

commodities. If assumptions are made concerning areal shapes and sizes of mineral resource targets, and if detection is clearly established if the target is intersected, then it would be feasible to devise procedures that would yield the number of boreholes that would be required to exhaust the resource potential of a unit area, assuming boreholes extend to some limiting depth.

Objectively estimating the probability of intersection of a repository's probability envelope by future exploratory drilling is currently impossible. This conclusion has been derived in part from my abstract analysis of the problem, but I have found little in the literature to alter this view. The issue of future exploration is largely unaddressed in the literature, except that resource potential studies are germane to future exploration.

Discussion of Currently Available Approaches

If objective estimation of repository probabilities is impossible, what are the alternatives to subjective probability estimates? First, the question of near-term drilling in the vicinity of proposed repository sites must be addressed. Is it feasible to drill an extensive series of exploratory holes beyond the periphery of a repository probability envelope to assess the geology and resource potential in the vicinity of a proposed site to some specified depth? If so, then the mineral resource potential could be estimated subjectively on the basis of a wealth of objective geological information. I have not otherwise addressed the issue of deep exploratory drilling in the vicinity of proposed repository sites, but I suggest that it be seriously considered.

If drilling a series of holes around the proposed repository site and its probability envelope is not feasible, could an approach be adopted that combines some of Griffiths's procedures with those used in the California Desert area by Lambie and others (1983)? Such an approach would use many different forms of geological information on a regional basis and would provide, as a conditioned estimate, the unit regional value of the proposed repository and vicinity. Results would be expressed on a relative scale, e.g., a large URV versus a small one. The results could be used to find locations of minimal URV for repository sites. It might be possible to extend such a study so that it is on a unit-rock-volume basis. Planning such a study would be a substantial effort in itself, perhaps requiring a man-year's effort. I am pessimistic that a URV approach will provide a satisfactory alternative to exploratory drilling.

Finally, a repository should be situated in a geological environment where the resource potential with respect to all possible commodities is not greater than average for Earth as a whole. If the potential is average or less than average for all resources, there should be minimum incentive for future exploration regardless of future economic conditions and technological advances and demands. This suggestion is similar to DOE's siting guidelines with regard to natural resources (DOE, 1984, Section 960.4-2-8-1).

I regard the proposal to drill an extensive series of exploratory holes as being beyond the scope of my study. If it is considered seriously, however, it should be preceded by regional resource studies. I suggest, therefore, that URV analysis be used for preliminary selection areas of apparent low resource potential, and that such areas then be ranked in terms of their other attributes with regard to suitability as repository sites. In turn, those areas chosen for exploratory drilling would be ranked in order of priority.

Planning an exploratory drilling campaign for a potential repository site is a major challenge in itself and is beyond the scope of this study.

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References

Abry, Claude G., 1975, "Geostatistical Model for Predicting Oil: Tatum Basin, New Mexico," Bull. Amer. Assoc. Petroleum Geologists, vol. 59, p. 2111-2122.

Agterberg, F. P., 1974, "Automatic Contouring of Geological Maps to Detect Target Areas for Mineral Exploration," Jour. Math. Geol., vol. 6, p. 373-375.

Arteaga, Daisy M., 1978, "Unit Regional Value of the Mineral Resources in Venezuela," Master of Engineering thesis, Pennsylvania State Univ., 91 pp.

Barlow and Haun, Inc., 1978, Appendices to Oil and Gas Production Reserves and Resources Report, (unnumbered), Minerals Division, Wyoming Department of Economic Planning and Development, 108 pp.

Berlanga, Juan M., and John W. Harbaugh, 1981, "Use of Seismic Data for Statistical Estimation of Outcome Probabilities of Complexly Faulted Structures in Tabasco Basin, Mexico," Bull. Amer. Assoc. Petroleum Geologists, vol. 65, p. 422-437.

Bloomfield, P., K. S. Deffeys, G. S. Watson, Y. Benjamin, and R. A. Stine, 1979, Volume and Area of Oilfields and Their Impact on Order of Discovery, Unpublished report, Princeton Univ., 53 pp.

Bonham-Carter, G. F., and C. F. Chung, 1983, "Integration of Mineral Resource Data for the Kasmere Lake Area, Northwest Manitoba, with Emphasis on Uranium," Math. Geol., vol. 15, p. 25-46.

Cargill, S. M., D. H. Root, and E. H. Bailey, 1980, "Resource Estimation from Historical Data, a Test Case," Math. Geol., vol. 12, p. 489-522.

Chung, C. F., 1983, "SIMSAG: Integrated Computer System for Use in Evaluation of Mineral and Energy Resources," Math. Geol., vol. 15, p. 47-58.

Chung, C. F., and F. P. Agterberg, 1980, "Regressive Models for Estimating Mineral Resources from Geological Map Data," Math. Geol., vol. 12, p. 473-488.

Collins, David R., 1985, "Changes in Drilling Density and Discovery Rates Through Time," Math. Geol., vol. 17, p. 375-394.

Davis, John C., and John W. Harbaugh, 1983, "Statistical Appraisal of Seismic Prospects in Louisiana-Texas Outer Continental Shelf," Bull. Amer. Assoc. Petroleum Geologists, vol. 67, p. 349-358.

Davis, John H., 1976, "Critical Values for a Measure of Contiguity of Anomalous Points in a Grid Survey," Math. Geol., vol. 8, p. 89-94.

Deffeyes, K. S., B. D. Ripley, and G. S. Watson, 1982, "Stochastic Geometry in Petroleum Geology," Math. Geol., vol. 14, p. 419-432.

Drew, Lawrence J., 1979, "Pattern Drilling Exploration: Optimum Pattern Types and Hole Spacings When Searching for Elliptical Shaped Targets," Math. Geol., vol. 11, p. 223-254.

Drew, L. J., J. H. Schuenemeyer, and W. J. Bawiec, 1979, "Petroleum Exhaustion Maps of the Cretaceous 'D-J' Sandstone Stratigraphic Interval of the Denver Basin," Misc. Invest. Ser., Map I-1138, US Geological Survey.

Drew, L. J., J. H. Schuenemeyer, and D. H. Root, 1980, "Petroleum Resource Appraisal and Discovery-Rate Forecasting in Partially Explored Regions--An Application to the Denver Basin," US Geological Survey Prof. Paper 1138A, p. A1-A11.

Eckstand, O. R., 1977, "Mineral Resource Appraisal and Mineral Deposits Computer Files in the Geological Survey of Canada," Math. Geol., vol. 9, p. 235-243.

Engelder, P. Richard, 1979, "Application of the Unit Regional Value Concept to a Study of the Mineral Resources of Australia," Ph.D. thesis, Pennsylvania State Univ., 357 pp.

Gill, Dan, and John C. Griffiths, 1984, "Areal Value Assessment of the Mineral Resources Endowment of Israel," Math. Geol., vol. 16, p. 37-89.

Gold, Michael, 1981, "Who Pulled the Plug on Lake Peigneur?" Science 81 Magazine, November.

Griffiths, John C., 1978, "Mineral Resource Assessment Using the Unit Regional Value Concept," Math. Geol., vol. 10, p. 441-472.

Griffiths, J. C., A. T. Watson, and W. D. Menzie, 1980, "Relationship Between Mineral Resource and Geologic Diversity," in A. D. Miall, ed., Facts and Principles of World Petroleum Occurrence, Canadian Soc. of Petroleum Geologists, Mem. 6, p. 329-341.

Harbaugh, John W., and Michel Ducastaing, 1981, "Historical Changes in Oil-Field Populations as a Method of Forecasting Field Sizes of Undiscovered Populations: A Comparison of Kansas, Wyoming, and California," Subsurface Geol. Ser. No. 5, Kansas Geological Survey, 56 pp.

Harbaugh, John W., John H. Doveton, and John C. Davis, 1977, Probability Methods in Oil Exploration, Wiley-Interscience, New York, 277 pp.

Kaufman, G. M., and J. W. Wang, 1980, Model Mis-Specification and the Princeton Study of Volume and Area of Oil Fields and Their Impact on Order of Discovery, Massachusetts Institute of Technology Energy Lab. Working Paper No. MIT-EL 80-003WP.

Labovitz, Mark Lang, 1978, "Unit Regional Value of the Dominion of Canada," Ph.D. thesis, Pennsylvania State Univ., 366 pp.

Labovitz, M. L., and J. C. Griffiths, 1982, "An Inventory of Undiscovered Canadian Mineral Resources," Econ. Geol., vol. 77, p. 1642-1654.

Labovitz, M. L., W. D. Menzie, and J. C. Griffiths, 1977, "COMOD: A Program for Standardizing Mineral-Resource Commodity Data," Comp. and Geosci., vol. 3, p. 497-537.

Lambie, F. W., J. W. Harbaugh, G. R. Kendall, and J. D. Juilland, 1983, "Classification of the California Desert for Geology-Energy-Mineral Resource Potential, A Geostatistical Classification," Tech. Note 359, US Bureau Land Management, 145 pp.

Lee, P. J., and P. C. C. Wang, 1983, "Conditional Analysis for Petroleum Resource Evaluations," Math. Geol., vol. 15, p. 349-361.

Lee, P. J., and P. C. C. Wang, 1985, "Probabilistic Formulation of a Method for the Evaluation of Petroleum Resources," Math. Geol., vol. 15, p. 163-182.

Meisner, J., and F. Demirmen, 1980, "The Creaming Method: A Bayesian Procedure to Forecast Future Oil and Gas Discoveries in Mature Exploration Provinces," Jour. Royal Stat. Soc., vol. 143, 17 pp.

Menzie, W. David, 1977, "The Unit Regional Value of the Republic of South Africa," Ph.D. thesis, Pennsylvania State Univ., 236 pp.

Meyer, Richard F., 1977, "Petroleum Resource Data Systems," Math. Geol., vol. 9, p. 281-299.

Meyer, Richard F., 1978, "The Volumetric Method for Petroleum Resource Estimation," Math. Geol., vol. 10, p. 501-518.

Nie, N. H., 1975, SSPS: Statistical Package for the Social Sciences, 2nd ed., McGraw-Hill Book Co., New York, 343 pp.

Omre, Henning, 1983, "The Combination of Subjective Information and Drill-hole Data for Estimating the Size of an Elliptical Target," Math. Geol., vol. 15, p. 477-481.

Root, D. H., and J. H. Schuenemeyer, 1980, "Petroleum Resource Appraisal and Discover-Rate Forecasting in Partially Explored Regions--Mathematical Foundations," US Geological Survey Prof. Paper 1138B, p. B1-B9.

Saul, Richard B., H. Clifton, Jr., and James R. Evans, 1971, Mines and Mineral Resources of Riverside County, California, California Div. of Mines and Geol., Sacramento, California, Unpublished report, 1016 pp.

Schuenemeyer, J. H., W. J. Bawiec, and L. J. Drew, 1980, "Computational Methods for a Three-Dimensional Model of the Petroleum-Discovery Process," Comp. and Geosci., vol. 6, p. 323-360.

Schuenemeyer, J. H., L. J. Drew, and W. J. Bawiec, 1980, "A Three-Dimensional Model to Predict Future Oil Discoveries in Spatially Connected Multiple Plays," Math. Geol., vol. 12, p. 459-472.

Shurygin, A. M., 1976a, "Discovery of Deposits of Given Size in Boreholes with Preselected Probability," Math. Geol., vol. 8, p. 81-85.

Shurygin, A. M., 1976b, "The Probability of Finding Deposits and Some Optimal Search Grids," Math. Geol., vol. 8, p. 323-330.

Singer, Donald A., 1971, "Multivariate Statistical Analysis of the Unit Regional Value of Mineral Resources," Ph.D. thesis, Pennsylvania State Univ., 210 pp.

Singer, D. A., 1975, "Relative Efficiencies of Square and Triangular Grids in the Search for Elliptically Shaped Resource Targets," US Geological Survey Jour. of Research, vol. 3, p. 163-167.

Singer, Donald A., 1976, "RESIN, a FORTRAN IV Program for Determining the Area of Influence of Samples or Drill Holes in Resource Target Search," Comp. and Geosci., vol. 2, p. 249-260.

Singer, D. A., and Lawrence J. Drew, 1976, "The Area of Influence of an Exploratory Hole," Econ. Geol., vol. 71, p. 642-647.

Singer, Donald A., and Frans E. Wickman, 1969, "Probability Tables for Locating Elliptical Targets with Square, Rectangular, and Hexagonal Point Nets," Penn. State Univ. Min. Sci. Exp. Sta. Spec. Pub. 1-69, 100 pp.

Smith, James L., and Geoffrey L. Ward, 1981, "Maximum Likelihood Estimate of the Size Distribution of North Sea Oil Fields," Math. Geol., vol. 13, p. 399-413.

Southern Pacific Company, 1964, Minerals for Industry in Southern California Summary of Geological Survey of 1955-1961, Southern Pacific Company, San Francisco, vol. 3, 242 pp.

US Bureau of Land Management, 1979, Occurrence of Industrial Minerals in the CDCA, Unpublished map, Desert Plan Staff, US Bureau of Land Management, Riverside, CA.

US Bureau of Mines, 1977, Mineral Industry Location System, Western Field Operations Center.

US Department of Energy, 1984, "Nuclear Waste Policy Act of 1982; General Guidelines for the Recommendation of Sites for the Nuclear Waste Repositories; Final Siting Guidelines," 10 CFR 960, Federal Register, vol. 49, p. 47714-47770.

US Environmental Protection Agency, 1985, "Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes, Final Rule," 40 CFR Part 191, Federal Register, vol. 50, p. 38066-38089.

US Nuclear Regulatory Commission, 1983, "Disposal of High-Level Radioactive Waste in Geologic Repositories, Technical Criteria, Final Rule," 10 CFR Part 60, Federal Register, vol. 48, p. 28194-28229.

Walsh, Deborah A., 1979, "An Assessment of the Mineral Resources of Ireland," M.S. thesis, Pennsylvania State Univ., 142 pp.

Watson, Alicia Tyler, 1977, "An Appraisal of the Mineral Resources of New Zealand," M.S. thesis, Pennsylvania State Univ., 129 pp.

White, David A., and Harry M. Gehman, 1979, "Methods of Estimating Oil and Gas Resources," Bull. Amer. Assoc. Petroleum Geologists, vol. 63, p. 2183-2192.

Chapter 3

CLIMATOLOGY*

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Abstract

The prediction of climatic variations over 10^3 to 10^6 years is an activity that is still in its infancy. Prediction methods are under development, but no study so far has combined all of the individual models necessary to estimate future climates at the spatial resolution required for the siting of repositories. This chapter describes (1) the major components of the climate system that must be considered in modeling its long-term variations, (2) models of the "slow" and "fast" processes of the climate system that can be used for climatic prediction, (3) the combination of modeling efforts required to estimate future climatic variations within the region of a proposed repository site, and (4) an outline of a method for estimating the uncertainties of those predictions.

Introduction

Research on long-term climatic variations has progressed rapidly over the past decade. Much of the stimulus for this work came from the publication of Understanding Climate Change--A Program for Action (US Committee for the Global Atmospheric Research Program, 1975). For variations on time scales of 10^3 to 10^6 years, key studies have revealed the controlling influence of the variations in solar radiation determined by variations of the earth's orbital elements (Hays and others, 1976; Imbrie and Imbrie, 1980; Berger and others, 1984). Further research has shown how the land--sea contrast translates seasonal radiation variations into major changes in monsoonal climates (Kutzbach, 1981; Kutzbach and Street-Perrott, 1985). This progress in

*This chapter reviews and evaluates techniques for assigning probabilities to climatic events and processes. This review and evaluation does not imply that the NRC has endorsed the use of the techniques discussed.

understanding and modeling long-term climatic variations has led to a few projections of future climates based on factors that influenced past climates (e.g., Imbrie and Imbrie, 1980). No comprehensive effort has been made, however, to predict the climates of the next 10^3 to 10^6 years, although theory and techniques are now available that can be applied to the task. This chapter evaluates (1) the current understanding of the climate system, (2) previous efforts at long-term climatic "prediction," (3) a potential method for prediction of regional climates over a time scale of 10^3 years and longer, and (4) the requirements for determining the uncertainties of those predictions.

The need for methods for predicting future climatic variations arises from the great impact these variations can have on other environmental systems (Goudie, 1983). Global-scale variations of the atmosphere, ice sheets, and oceans that typify the climatic variations of the Quaternary Period have been accompanied by regional- and local-scale changes in hydrology and ecology. Because variations of the hydrologic system are driven by climatic variations (e.g., Street-Perrott and others, 1983), the course of future climatic variations becomes an important consideration in evaluating the stability of a proposed repository.

The connection between climate and hydrology is particularly evident in the Great Basin, where extensive pluvial lakes repeatedly formed and disappeared during Quaternary time (Smith and Street-Perrott, 1983; Webb and others, 1979). In the Great Basin, tectonic and volcanic activities have resulted in the topographic closure of the majority of watersheds. This closure implies that the repeated growth and shrinkage of the pluvial lakes depended entirely on the balance between precipitation and evaporation within the closed basin.

Smith and Street-Perrott (1983) provided an extensive survey of paleolake levels throughout the Great Basin over the past 10^4 years. The connection between the variation of lake levels and climate is well established and broadly accepted (Kutzbach, 1980; Benson, 1981; Street-Perrott and Harrison, 1984; Kutzbach and Street-Perrott, 1985); however, the exact conditions favoring the existence of pluvial lakes are not precisely known, nor is the relationship between variations of the ground- and surface-water systems.

Ground-water aquifers often encompass large basins that include several sources of recharge (Bredehoeft and others, 1982; Winograd and Thordarson, 1975); thus, the hydrologic variations responsible for the development of pluvial lakes could add significant volumes of water to the ground-water system. Discussion of the influence of climatic variations on the surface- and ground-water systems is beyond the scope of this volume.

Evaluation of the predictability of climatic variations that occur on long time scales ($>10^3$ years) requires consideration of the components of the climate system that vary at those scales, the nature of potential external controls of those variations, and the degree to which observed climatic variations at those scales can be explained. A review of the components of the climate system is a key prerequisite for an analysis of climate prediction at long time scales.

Components of the Climate System

Basic Components. The components of the climate system are the atmosphere, the hydrosphere, the cryosphere, the surface lithosphere, and the biomass (Figure 3-1; Gates, 1981). Individual components, such as ice sheets, land surface, mixed-layer and deep ocean, have different thermal characteristics and response times. The atmosphere responds relatively rapidly to changes in external controls, the mixed layer of the ocean more slowly, and the deep ocean and continental ice sheets extremely slowly (Saltzman, 1985, Table 2). Individual climate variables may be categorized into (a) those that describe the boundary conditions, or the external controls, of the climate system, (b) those that describe slowly varying components, and (c) those that describe fast-response components.

Individual components are related to one another through transfers of mass and energy. These transfers occur along many pathways and involve many feedback mechanisms. One result of such interconnectedness (Saltzman, 1983, p. 203) is the possibility that variations in a particular component of the climate system may result from purely internal, "free" variations, e.g., short-term climatic variations like those described by Namias (1975), as opposed to external "forced" variations, like those cause by insolation. Because they occur in the absence of external changes in the system, these free variations are inherently unpredictable in detail, although their statistical properties can be described (Kominz and Pisias, 1979). In other words, the exact record of a particular component of the system as it participates in such free variations may not be describable, but the general characteristics of the record (its variability or persistence, for example) may be. The opportunity for such internally driven variations to exist thus assures us that the success of explicit long-term climatic predictions has an upper limit.

Controls of Climatic Variations. The climate system has several external controls; these include the incoming solar radiation, the composition of the atmosphere, and the arrangement and size of the continents. There are additional controls, but their explicit definition depends on the context within which the climate system is being considered. At shorter time scales, i.e., shorter than 10^4 years, the size (volume, area, and elevation) of the ice sheets and the temperature of the oceans may also be regarded as external controls, because their response times are that long or longer. The relevant set of external controls thus depends on the time scale of climatic variation of interest. For short time scales, the controls may include slowly varying components of the climate system that at longer time scales can be regarded as dependent, internal components of the system.

An additional consideration that complicates the explicit definition of controls of climatic variations is that for some components of the climate system, either their role in the system is imperfectly understood, or their future variations are inherently unpredictable. The concentration of CO_2 in the atmosphere is typical of such a component. During Quaternary time, the concentration of CO_2 in the atmosphere has varied in a fashion consistent with global climatic variations (e.g., Shackleton and Pisias, 1985). It is

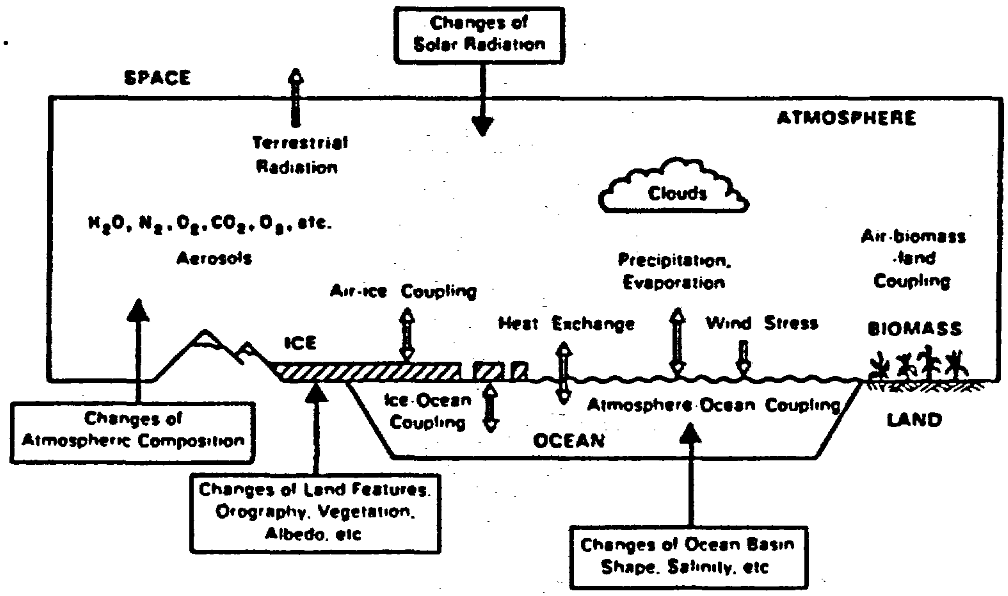


Figure 3-1. Principal components of the climate system and their interactions (Figure 1 in Gates, 1981, after US Committee for the Global Atmospheric Research Program, 1975).

impossible to state, however, whether CO_2 variations contributed to the global climatic variations, or were driven by them, or both. During the past century, the concentration of CO_2 in the atmosphere has increased as a result of industrialization, a process clearly outside of the climate system whose future course is inherently unpredictable (Kellogg and Schware, 1981).

In a similar fashion, the dust loading of the atmosphere can be considered as an externally determined variable, as in the case of volcanic eruptions (e.g., Bryson and Goodman, 1980) or nuclear wars (Committee on the Atmospheric Effects of Nuclear Explosions, 1985). In the case of "Dust Bowl"-generated dust, however (e.g., Heathcote, 1983), the dust loading is at least in part an internally determined component of the climate system. Both dust and CO_2 concentration are therefore usually considered as "prescribed" boundary conditions, because the nature of their variations within the climate system are imperfectly known.

Temporal and Spatial Scales of Climatic Variability

Temporal Variations. A "powers-of-ten" approach effectively illustrates the magnitude of climatic variations at different time scales (for example, US Committee for the Global Atmospheric Research Program, 1975, Figure A.2; Kutzbach, 1976, Figure 1). At the time scale of 10^2 years (e.g., the past 100 years), the mean temperature of the northern hemisphere land surface has varied about 0.5°C (Figure 3-2); over the past 10^3 years by about 1.5°C; and over 10^4 years or longer (i.e., the Quaternary Period) by about 10°C. As the length of time considered increases, so does the range of climatic variation.

Spatial Variations. Climatic variations at a particular location are embedded in a hierarchy of larger-scale variations. Precipitation at a point, for example, is generated by passing weather systems with life spans on the order of days. These systems are in turn embedded in hemispheric-scale atmospheric circulation anomalies with life spans on the order of months or seasons (Namias, 1975). Finally, large-scale circulation features in their turn are related to hemispheric or global-scale variations in the energy balance of the earth--atmosphere system. A climatic change in a given region may therefore have a proximate cause, such as a change in the duration of different air masses or the relocation of a storm track, that in turn is related to an ultimate cause of hemispheric or global extent.

The hierarchical nature of climatic variation implies that the climatic record of a particular region cannot be explained (and, hence, predicted) in isolation. Local climatic variations are indeterminate with respect to larger-scale variations: the same local record could be generated by a range of larger-scale variations. Climate prediction must therefore proceed in a "top-down" fashion--from large-scale, external controls, to the smaller-scale, dependent responses.

Climate Prediction

Classes of Climate Prediction. Two different classes of climatic prediction can be envisaged, one in which the time history of the climate

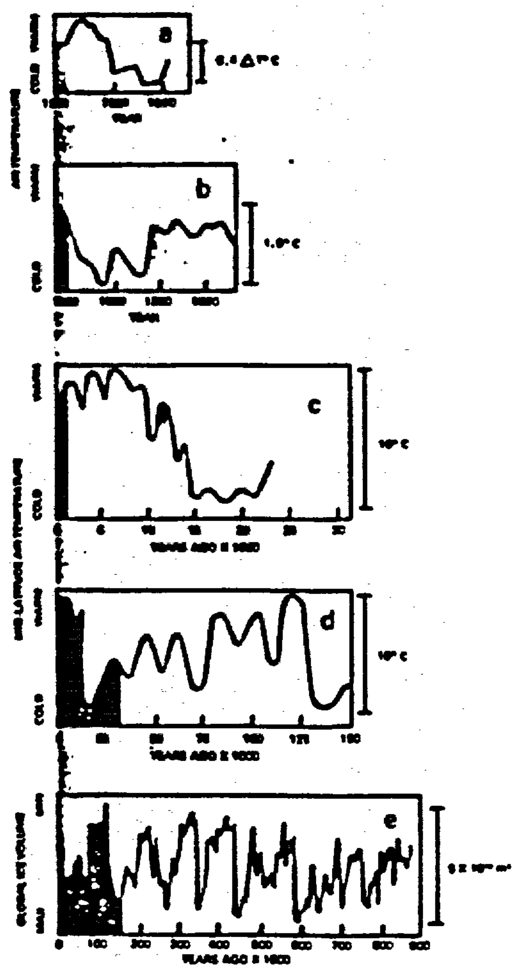


Figure 3-2. General trends in global climate for various time scales ranging from 10^2 to 10^6 years (Figure 1 in Webb and others, 1985, after US Committee for the Global Atmospheric Research Program, 1975).

variable of interest is predicted in an _explicit_ fashion, and the second in which only the _statistical_ properties (e.g., the average, range, variability, persistence, etc.) over some interval are predicted. Either kind of prediction requires specification of the controls of the dependent climatic variable of interest and of the model linking the controls to the variable. The specific nature of the controls and model depends, however, on the context of a particular prediction problem.

When the climate model can be completely specified, and when the controls are known or predictable, then the first kind of prediction is possible. Such a situation is not likely to arise for the temporal and spatial scales of prediction required to evaluate the stability of repositories. Uncertainties exist in both the nature of the controls and the models, and these uncertainties will not be reducible by a simple increase in modeling effort. Some of the external controls of the climate system, such as the inputs of solar radiation that are determined by the orbital variations, are predictable, but other controls that influence long-term climatic variations, such as solar output and atmospheric composition, are not. Similarly, while some climate models exist that can, for example, relate global ice volume to orbitally determined radiation variations (Imbrie and Imbrie, 1980), models of many other components of the climate system are not available. Moreover, the opportunity for feedback to occur among different components of the climate system (e.g., Saltzman, 1983; Gates, 1981) makes it unlikely that a comprehensive model of the climate system could ever be completely specified. The uncertainties in both controls of climatic variations and models of the climate system thus make possible only the second kind of prediction, prediction of the statistical properties of a particular climate variable.

Climate Prediction at Different Time Scales. Only at the shortest of time scales ($\leq$10 years) can climate prediction of the first kind be regarded as "operational" in any sense (Namias, 1975). Short-term prediction of temperature and precipitation patterns over, say, the United States exploits the dependence of surface climate patterns on the characteristics of the large-scale atmospheric circulation. Predictions are made by first extrapolating circulation anomalies (the climatic controls) into the forecast period, and then using empirically derived relationships (the climate model) to transform the circulation predictions into predictions of surface climate variables. Explicit prediction of time series of temperature and precipitation is possible only to the extent that the controlling large-scale atmospheric circulation features are predictable. Currently, such predictions have been attempted only up to a season ahead, and considerable uncertainty remains in those predictions.

Medium-term climatic predictions (10 or 100 years) currently are being developed for assessing the impact of rising CO_2 concentrations in the atmosphere (Schlesinger, 1984). These assessments use the full variety of climatic models and are used to predict the statistical attributes of the altered climate systems, as opposed to the specific record over this time scale. In a typical example, Hansen and others (1984) used a low-resolution, three-dimensional model of the climate system to predict the variation of hemispheric mean temperature over the next 100 years in response to variations in such boundary conditions as atmospheric CO_2, dust, and insolation.

Atmospheric general circulation models can be used to infer the spatial patterns of the response to elevated CO_2. Most of the models used at this time scale are equilibrium models--those that give a snapshot view of conditions after a change in boundary conditions--as opposed to transient models that attempt to show the course of adjustment to the new equilibrium (Schneider, 1984). Schlesinger (1984) noted that while models tend to show similar responses of globally averaged temperature, they differ on the spatial patterns of the response. In any case, even at a scale that is short relative to the scales of interest here, climatic prediction of the first kind is not possible.

At longer time scales (>10^3 years), specific examples of climatic prediction are rare, and these are directed more toward explaining the evolution of climate over the long run than forecasting a specific course of climatic variation. As will be described below, climatic prediction at long time scales has been concerned mainly with the prediction of the boundary conditions and the slowly varying components of the climate system (e.g., global ice volume). Specific models linking external controls with dependent variables are either simplified or borrowed from studies at shorter time scales.

Potentially Predictable Events and Processes. As the time scale increases, the temporal and spatial resolution of the predictable components of the climate system decreases. Over the shortest time scales, the specific values of climatic variables at individual locations can be predicted. As the time scale increases, specific values at a particular location can no longer be predicted, and at the longest time scales, only the long-term averages of greatly aggregated climatic variables (e.g., average hemispheric temperature, or global ice volume) have any potential for prediction.

The climate system itself offers no intrinsically defined events that are potential targets for prediction in the same way that a volcanic eruption or meteorite impact is an event. Over the long time scale (>10^3 years) even glaciation is not an event; at this scale, global ice volume is a continuously varying component of the climate system. While a particular location can be considered to be glacierized or not, it exists under a glacial climate long before ice reaches there. The specific climatic events for which probabilities of occurrence are sought must therefore be defined by the user of the predictions.

Climatic Variations on the Quaternary Time Scale (10^3 to 10^6 Years)

Analyses of climatic variations at the time scale of 10^3 to 10^6 years generally follow one of two interrelated approaches. In a data-oriented approach, individual, or networks of individual, records of paleoclimatic evidence are interpreted in paleoclimatic terms (see, for an extensive review, Bradley, 1985). In a modeling approach, climate models, initialized using reconstructed boundary conditions, are used to make inferences about the structure of the past climates (e.g., Kutzbach, 1981). The data-oriented approach can be thought of as a "bottom-up" analysis of past climates, in that a large body of individual elements of paleoclimatic evidence is amassed to draw conclusions about the general state of the climate system at a particular time. The modeling approach, in contrast, can be thought of as a "top-down" analysis of climate, in that general, or large-scale, boundary conditions are used to initialize a model that then may give a spatially disaggregated simulation of climate.

The two approaches are related in that paleoclimatic data are necessary for specifying the boundary conditions of the models and for model validation experiments (CLIMAP Project Members, 1976, 1981; Peterson and others, 1979). The models in turn may be used to evaluate the physical consistency of sometimes disparate compilations of paleoclimatic evidence (Kutzbach and Street-Perrott, 1985).

For the purposes of climatic prediction on the long time scale, a top-down, modeling-type approach must be used, and the design of such an approach can make use of the experience gained from applications to the paleoclimatic record. Analyses of paleoclimatic data must also be an element of any climatic prediction scheme, because the data can illustrate the range and nature of climatic variations on the long time scale and are necessary for model validation (Webb and others, 1985).

Focus of This Chapter

The next section reviews methods of paleoclimatic prediction that have been applied on the long time scale (>10^3 years). A workable approach for climatic prediction is discussed in a subsequent section.

We found only six studies that have attempted to predict climate explicitly over the long time scale (>10^3 years). These include one part of a general review of climatic change (US Committee for the Global Atmospheric Research Program, 1975), in which the statistical properties of past variations were used to derive the probabilities of occurrence of climatic variations of different magnitudes. Two other studies (Petersen and Larsen, 1978; Kanari and others, 1984) used empirically derived statistical models to forecast the future record of two long climatic series. Berger (1977) used a simple energy-balance climate model to forecast future values of average annual temperature from deterministic variations of the earth's orbital elements. Kukla and others (1981) used a heuristically determined function of the orbital elements to predict a composite climatic series. Imbrie and Imbrie (1980) employed a simple differential equation model to predict future values of global ice volume on the basis of variations in the orbital elements.

The range of efforts that have attempted to predict climate implicitly is much broader, however, and includes virtually any study that focused on modeling or explaining Quaternary climatic changes. The methods of climatic prediction for the 10^3-year time scale and longer can be divided into those derived from analyses of paleoclimatic data and those derived from climate models. In addition to the six explicit attempts, the principal efforts in the broader group will be examined here.

Methods of Climate Prediction for 10^4 Years

Paleoclimatic-Data-Based Predictions

Prediction of the nature of future climatic variations on the basis of paleoclimatic variations assumes similitude between the characteristics of the past record and the desired future one. The nature of past climatic variations can provide information about the nature of future variations only if the operation of the climate system can be expected to remain similar through time. Study of the past climate can yield only general indications of the future climate; explicit forecasts of the course of future climatic variations are not possible, except as simple extrapolations of past behavior. Because the boundary conditions of the climate systems are not likely to undergo a similar evolution over the next 10^4 years as they have in the past 10^4 years, predictions based on analysis of the paleoclimatic record alone will always contain some uncertainty. Climate predictions based on paleoclimatic evidence can be divided into those that are simply descriptive and those that employ a formal analysis of the statistical nature of the paleoclimatic variations.

Predictions Based on Descriptive Studies. Two examples of "predictions" of future climatic variations are given by Lamb (1982, Chapter 17) and Budyko (1982, Chapter 6). Both authors examined the record of climate change. Lamb emphasized the role of climate in history, and Budyko focused on the variations through time of the energy balance of the earth and atmosphere. Both presented predictions in descriptive, qualitative terms, summarizing their own inferences and drawing on the conclusions of other publications. Neither offered an explicit forecast of the future evolution of the climate system, but instead described in general terms the range of likely possibilities.

Kukla and Matthews's (1972) prediction was also based on largely descriptive study of variations during Quaternary time. They drew attention to the tendency for past interglacial intervals to last about 10^4 years and noted that the present one had lasted about that long.

The largely descriptive approach represented by these studies has utility in formulating climate predictions over the long time scale because it focuses attention on the most evident features of the record of the climate system (such as the glacial/interglacial cycles of the Quaternary Period). Such features are likely to be the most robust in future variations, and it is likely that the greatest part of the actual predictability of future climates can be attained by such simple means.

Predictions Based on Statistical Analyses. Climate predictions based on statistical analyses of past climatic variations more directly invoke the assumption that future variations will be like those of the past. By describing the statistical nature of past variations, the nature of future ones can be inferred. In a sense, any analysis of the statistical properties of a climate record can be used for climate prediction. The discussion here will focus on analyses of paleoclimatic records that cover long time scales.

Statistical analyses of time series of paleoclimatic records can be classified into two types: those focusing on the frequency-domain aspects of the series and those focusing on the time-domain characteristics (Imbrie, 1985). Frequency-domain analyses employ the methods of spectral analysis of time series (Priestley, 1981) to describe the variability of a time series as a function of the frequency or period of variation. Time-domain analyses are directed toward building models that explicitly describe the nature of the temporal evolution of a series, i.e., the interval-to-interval persistence or "memory" in the series, or the leading or lagging relationships between series (Box and Jenkins, 1976). The product of a time-domain analysis is a model that explicitly links the current level of a time series with the past levels of the series, or additionally, the current and past levels of related series. This product is easily adaptable for forecasting. The two types of analyses are related because the parameters of the time-domain model can be used to estimate the frequency-domain spectrum and vice versa (Priestley, 1981, p. 211). Both statistical prediction methods probably have their greatest utility in predicting the future variations of the slowly varying external controls of the climate system. Although analysis and prediction of local variations are possible, they will suffer from the same indeterminacy described earlier for the spatial hierarchy of climatic variations.

Analyses of the spectrum of paleoclimatic time series include those by Kutzbach and Bryson (1974), Mitchell (1976), Hays and others (1976), and Pisias and Moore (1981). Kutzbach and Bryson (1974) assembled a composite spectrum of climatic variations for time scales ranging from 1 to 10^5 years from separate analyses of historical, isotopic, and botanical climatic records. The overall shape of the spectrum indicates that longer-period variations are similar to those of a "red-noise" time series--one in which the range of variation increases with the span of time considered.

The information contained in the spectrum of a time series allows the rates and probabilities of occurrence of climatic changes to be inferred. One such analysis, that by the US Committee for the Global Atmospheric Research Program (1975), is described in Appendix 6.1. This analysis is particularly important because it illustrates how probability statements about specific climatic variations can be derived from paleoclimatic data.

Time-domain analyses of paleoclimatic time series include those by Petersen and Larsen (1978) and Kanari and others (1984). Both these studies explicitly predicted the future course of the series under consideration. Petersen and Larsen (1978) examined a 700,000-year-long record of oxygen isotope variations (Figure 3-3), and Kanari and others (1984) a 500,000-year-long composite record of pollen data (Figure 3-4). In both analyses, models from the family of autoregressive-moving average (ARMA) models (Box and Jenkins, 1976) were fitted to the data and used to forecast values of the series for future time steps. As is true for all predictions based on statistical models, several sources of uncertainty are attached to these forecasts. In particular, uncertainty arises in the selection of the form of the model and the estimation of the values of its parameters. The variance of the forecasts from such a model increases rapidly with the lead time of the forecast (Box and Jenkins, 1976, Chapter 5), and so predictions are possible for only a limited time into the future relative to the duration of the series.

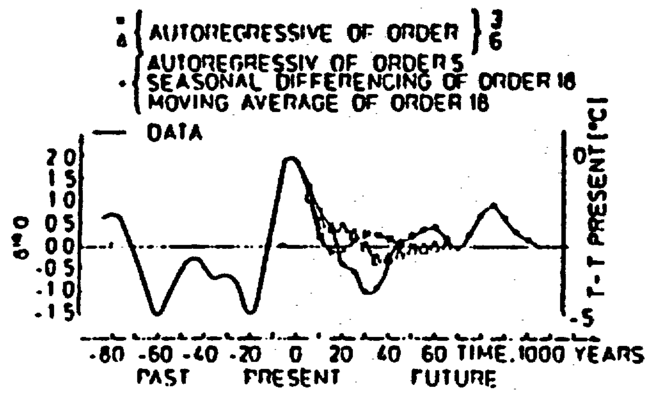


Figure 3-3. Past and predicted future variations of an ^{18}O series (Petersen and Larsen, 1978, Figure 7).

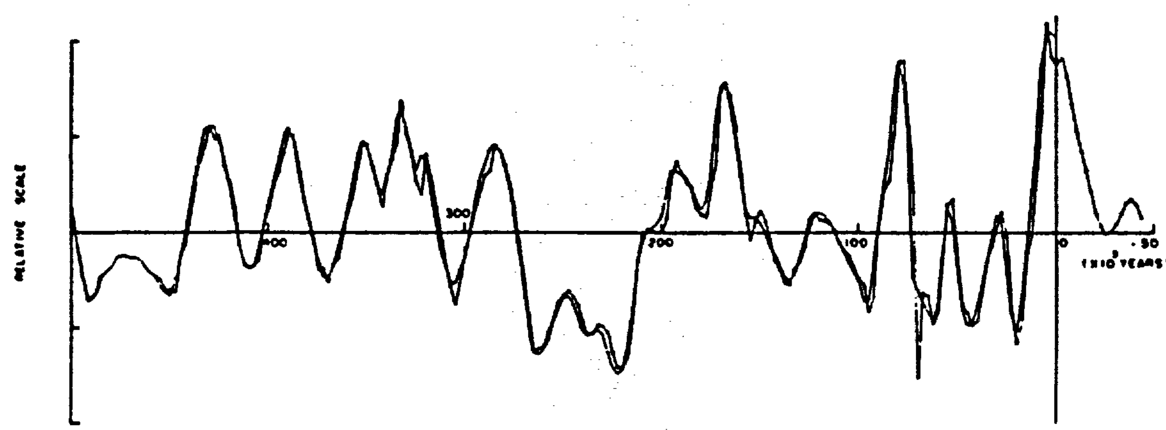


Figure 3-4. Past and predicted future variations of composite records of pollen data from Lake Biwa (Kanari and others, 1984, Figure 2).

Climate-Model-Based Predictions

Climate models can be classified into those that describe fast-response components of the climate system, such as the atmosphere, surface-energy and water balances, and mixed layer of the ocean, and those that describe slowly varying components, such as the ice sheets and deep ocean (Saltzman, 1985). At time scales shorter than 10^4 years, slowly varying components may be properly regarded as external, "boundary-condition-like" factors.

Models of the Fast-Response Components. Models of the rapidly varying parts of the climate system, chiefly the atmospheric ones, can be divided into two groups (Saltzman, 1985). The first group explicitly represents the three-dimensional structure of the atmosphere, and in a sense, simulates day-to-day variations of the weather. The second group instead simulates the longer-term, spatially averaged weather, i.e., the climate. The first group of models includes the atmospheric general circulation models (AGCMs or GCMs) and the second contains the statistical-dynamical models (SDMs) in general, and the energy-balance models (EBMs) in particular.

Atmospheric general circulation models (GCMs) attempt to represent the three-dimensional structure of the atmosphere and simulate the day-to-day variations of weather by solving basic equations that govern the motion of the atmosphere over a three-dimensional grid (Meehl, 1984). Detailed information on the state of the atmosphere and the underlying surface over that grid is required to initialize the models. Whereas many specific physical processes are explicitly represented in such models, others are prescribed to remain at set levels and are not free to interact with other elements of the model. Because the time constants of the oceans are so long relative to the atmosphere, current computer capabilities make it prohibitively expensive to routinely simulate ocean temperature and circulation in parallel with the atmosphere. In consequence, ocean surface temperatures are often prescribed at climatic-mean values. GCMs incorporating interactive (with the atmosphere) mixed-layer oceans are currently being applied, but models with a fully coupled ocean and atmosphere are still under development (Meehl, 1984).

In practice, GCMs provide snapshot views of atmospheric components of the climate system under fixed or limited variations (i.e., the seasonal cycle) of the boundary conditions, because the models are run at most for several hundred model-days at a time. Longer integrations are possible, but then numerical instabilities in the models' equations become important.

Pioneering applications of GCMs for the simulation of paleoclimates include those by Williams and others (1974), Gates (1976a, 1976b), and Manabe and Hahn (1977). In these applications, the models were initialized using ice-age characteristics of the land and ocean surfaces (e.g., CLIMAP Project Members, 1976). More recent applications of a similar nature include those by Manabe and Broccoli (1985) using a GCM with a mixed-layer ocean and by Hansen and others (1984).

Possibly the most extensive applications of GCMs in a paleoclimatic context have been made by Kutzbach and his co-workers using both a low-resolution

GCM (Kutzbach, 1981; Kutzbach and Otto-Bliesner, 1982) and the higher resolution NCAR CCM (National Center for Atmospheric Research Community Climate Model) (Kutzbach and Guetter, 1984; Kutzbach and Street-Perrott, 1985). These experiments allowed study of how the model responded to variations of solar radiation input, ocean surface temperature, extent of sea ice, and the size of the Laurentide ice sheet during the past 18,000 years (Figure 3-5).

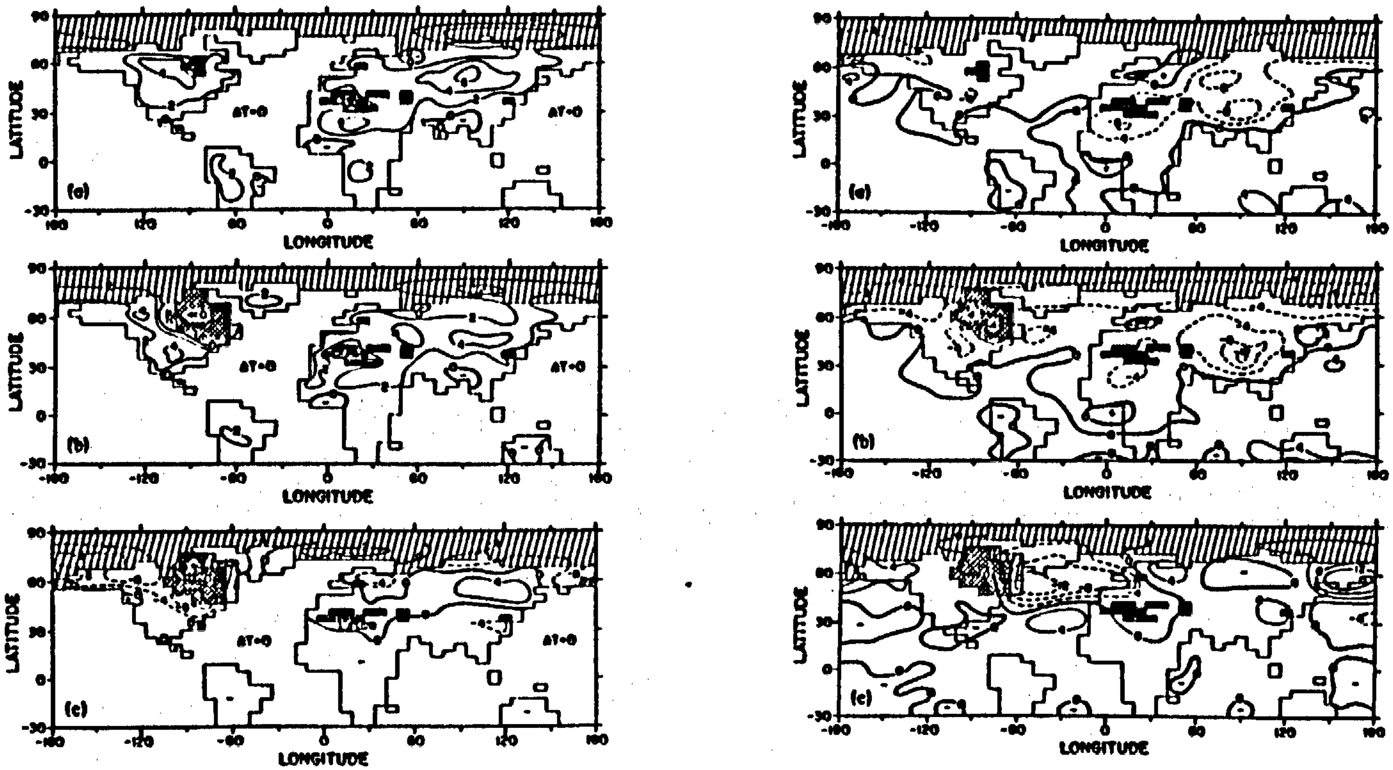
In all these studies, the models were not used in and of themselves to interpret or reconstruct past climates. Instead, they were used to infer the spatially varying aspects of climate that would be likely under specific boundary conditions and states of the slowly varying components of the climate system. The potential of these models for climate prediction lies in their ability to disaggregate the global-scale components of the climate system.

A second group of climate models that attempts to represent the variations of the rapidly varying components of the climate system has been used in a paleoclimatic context. These include the energy-balance models (EBMs), which are members of the broad class of statistical-dynamical models (Saltzman, 1978). EBMs consider long-term, wide spatial averages of elementary heat-balance-related components of the climate system. In comparison with GCMs, EBMs are relatively simple in terms of their detail and requirements for initial data and are much less costly to design and use. Introductory reviews of EBMs are given by Meehl (1984) and Ghil (1981), and more comprehensive reviews by Saltzman (1978) and North and others (1981).

Energy-balance models are used in paleoclimatic contexts by examining the response of the highly aggregated climate of the model to changes in the external controls. The external control most often considered is the input of solar radiation, as modified by temporal changes in the earth's orbital elements (see for example, North and others (1984) and Adem and others (1984)). The object of such experiments is to examine how such climatic variables as zonally averaged (averaged within a latitude band around the globe) temperature or the latitude of permanent snow cover respond to variations in solar radiation.

Berger (1977) used Sellers's (1969) early model to simulate zonally averaged annual mean air temperature over the past and the next 200,000 years (Figure 3-6). The model was driven by the temporal variations of solar radiation inputs over that interval. Although the results of the paleoclimatic simulations by Berger only roughly corresponded to the known record (the magnitude of the climatic response was small, and the large thermal lags of the ice sheets and oceans were not explicitly taken into account), this application illustrates the possible role that such models could play in climatic prediction.

The utility of the above models of the fast-response components of the climate system in a comprehensive scheme for predicting future climatic variations is derived from their applicability in providing a "snapshot" view of the climate system under a particular set of boundary conditions and state of slowly varying components. To portray the behavior of the climate system as it evolves through time in dynamic equilibrium with changing boundary



Land-Surface Temperature

Sea-Level Pressure

Figure 3-5. Simulated land-surface temperature and sea-level pressure differences between 9000 years B.P. and today for (a) July, with no North American ice sheet, (b) July with the North American ice sheet, and (c) January with the North American ice sheet (Kutzbach and Guetter, 1984, Figures 1 and 3).

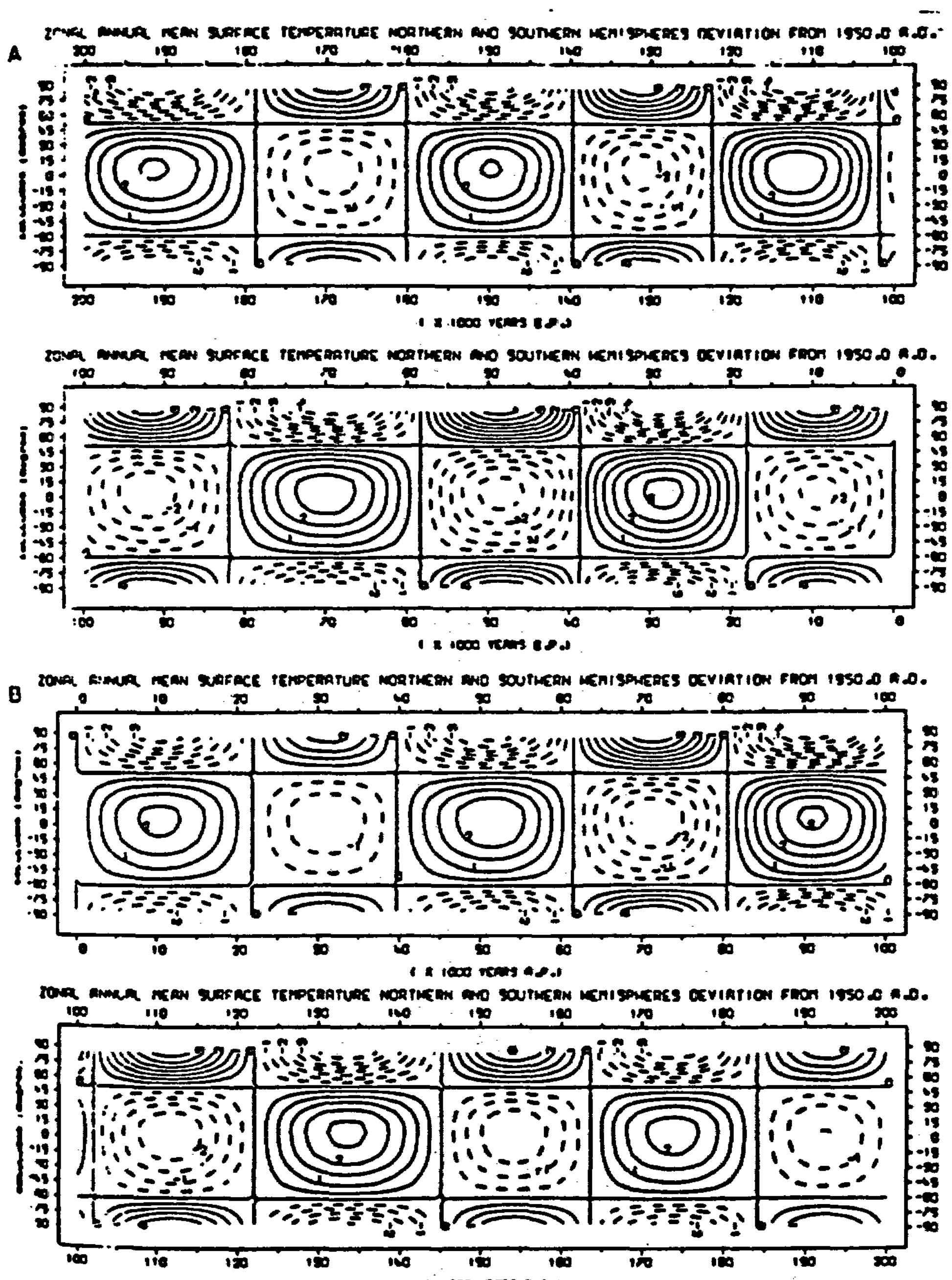


Figure 3-6. **Simulated past and predicted future variations in zonal mean temperature (expressed as deviations from the modern values) (Berger, 1977, Figure 4).**

conditions, it is necessary to consider models of the slowly varying components such as the ice sheets and deep ocean that, along with the boundary conditions, are the generators of long-term climatic variations (Saltzman, 1985).

Models of the Slowly Varying Components. Saltzman (1985) grouped models of the slowly varying components of the climate system into two categories. First, a quasi-deductive group of models explicitly derives, for example, models of the ice sheets, ice shelves, deformable bedrock, and deep ocean from basic physical principles. Second, a more inductive group of models seeks a physically reasonable model that produces results consistent with the observational records of paleoclimatic variations. The distinction between these two groups is somewhat blurred. An alternative way to consider models of the slowly varying components of the climate system is to arrange them along a gradient from those models that represent the physics of a process as explicitly as possible to those models that are essentially empirically determined "black-box" models of a component of the climate system.

The quasi-deductive group of models is typified by a variety of somewhat-related models that represent how ice sheets, ice shelves, sea level, and underlying bedrock respond to variations of solar radiation (see for review, Oerlemans, 1982, 1984). Pollard's (1983) model, for example, simulates Northern Hemisphere ice-sheet thickness and bedrock elevations beneath the ice. It uses solar radiation as input and includes such processes as bedrock deformation beneath and in front of the ice sheet, ice-shelf calving, and other processes of ice-sheet dynamics. The main accomplishment of Pollard's (1983) model was to simulate 100,000-year-long oscillations of the ice sheet, mainly as a result of including the effects of bedrock deformation and ice calving. While these models contain physically explicit representations of many important processes involved in the growth and decay of ice sheets, they still contain important parameters that are determined only empirically. Saltzman (1984, 1985) argued that we may never be able to completely capture the deterministic physics that underlie the slow variations of the climate system.

An alternative approach, therefore, may be to devise models for the slowly varying components of the climate system that are, in a sense, as geologically reasonable as they are physically explicit. An example of such an inductive model is that given by Imbrie and Imbrie (1980), which attempts to represent variations of global ice volume as forced by variations of the earth's orbital elements. Their model is a simple differential equation governing change in the total volume of ice, expressed as a function of the current volume and the orbital forcing (see Appendix 6.2). The model has five empirically determined parameters, three tuning the contributions of the orbital elements to the ice volume, and two representing response times of the ice sheet that differ between ice growth and ice decay phases--a geologically reasonable development. The ice record simulated by the model agrees well with the observed record over the past 250,000 years, and Imbrie and Imbrie (1980) used deterministic future values of the orbital elements to project the ice volume series 100,000 years into the future (Figure 3-7).

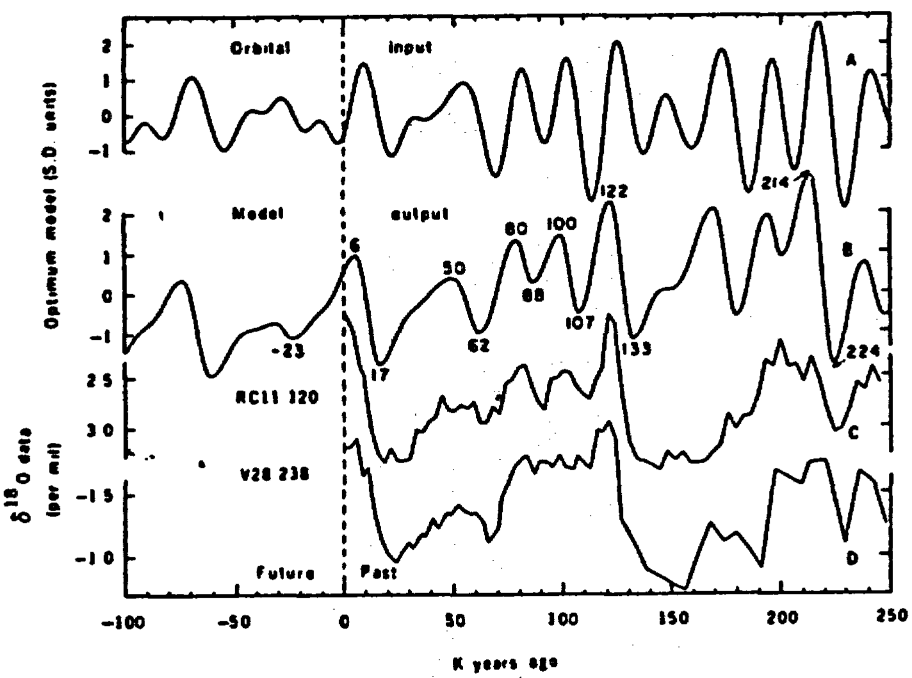


Figure 3-7. Orbital input and past and predicted future ice volumes simulated by the Imbrie and Imbrie (1980) model, and observed ^{18}O records (Imbrie and Imbrie, 1980, Figure 7).

In a similar spirit, Kukla and others (1981) derived an "astronomical climate index" generated by an empirical function of the orbital elements. The function was chosen to yield a time series of the index that matched a composite climatic record consisting of pollen, sea-level, and oxygen-isotope records. Using the orbital elements as input, they generated a series of the index for the past and future 10^6 years (Figure 3-8).

Saltzman and Sutera (1984) and Saltzman and others (1984) have developed an inductive model that is slightly more elaborate than Imbrie and Imbrie's (1980). This model generates series of both continental and marine ice masses (as opposed to global ice in the Imbrie and Imbrie model) and ocean temperature. A remarkable feature of the model is the ability of nonlinear feedbacks among these components to generate, under random forcing alone, free variations of the model output with a characteristic 100,000-year oscillation. The phase relationships among the output series were incorrect, however. Saltzman and others (1984) showed that when forced with realistic values of solar radiation, the phase relationships among the series locked in in a manner consistent with the observed record. The ice-mass record generated is also in substantial agreement with the observed. The role of these inductive models in climatic prediction over the long time scale lies in their ability to account for much of the long-term variations in the global-scale, slowly varying elements of the climate system.

<u>Summary.</u> A wide variety of approaches has been used in the analysis of climatic variations on the long time scale, but explicit attempts at climatic prediction are relatively few. It is fair to say that <u>no</u> studies exist in which the specific objective was development of a procedure for prediction of future climatic variations over the long time scale. Lamb (1982) and Budyko (1982) described in general terms the likely future variations of the climate system but did not offer explicit predictions for the time scale of interest here. Of the six studies among those reviewed above where explicit predictions were attempted (Table 3-1), only one (Kanari and others, 1984) focused on what could be regarded as a local climatic signal. The US Committee for the Global Atmospheric Research Program (1975) considered very generalized climatic records and variations. Petersen and Larsen (1978) and Imbrie and Imbrie (1980) predicted global ice volume, Berger (1977) estimated zonally averaged annual temperature, and Kukla and others (1981) predicted a global-scale climatic index. Locally or regionally relevant predictions are currently possible only for the fast-response components of the climate system. Although no specific methods for producing locally or regionally relevant climatic predictions over the long (>10^4 year) time scale have so far been developed, the nature of a workable approach can easily be envisioned and is described in the next section.

Critical Analysis of Prediction Methods

An Approach to Long-Term Prediction

Consideration of the components of the climate system, the controls over their variations through time, and the approaches taken in analyzing those

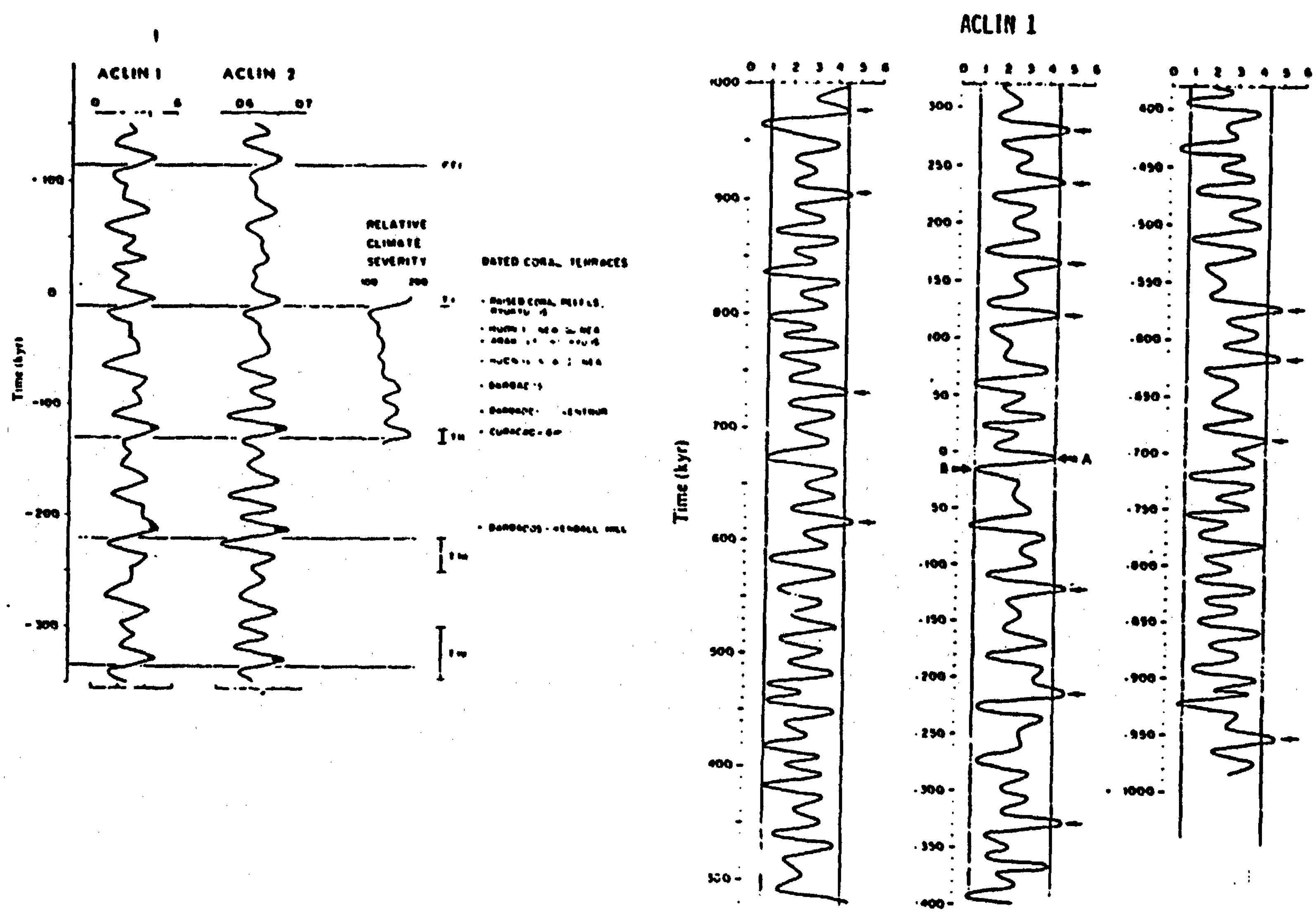


Figure 3-8. Plots of the astronomical climate index for the past and future 10^6 years (Kukla and others, 1981, Figures 3 and 4).

Table 3-1. Characteristics of climate prediction methods

	NAS (U.S. Comm. GARP, 1975)	Petersen and Larsen (1978)	Kanari and others (1984)	Berger (1977)	Imbrie and Imbrie (1980)	Kukla and others (1981)
Type of model	statistical	statistical	statistical	energy balance	"inductive"	"inductive"
Required input/ data analyzed	spectra of climatic series	^{18}O series (ice volume)	composite pollen chronology	insolation series	insolation/ ^{18}O series (ice volume)	insolation/ composite climatic series
Generated output	probability statements	ice volume	pollen series	ann. mean temperature	ice volume	climatic index
Scale of output	varies	global	regional	zonal ave. (global)	global	global
Data available for method	yes	yes	limited	yes	yes	yes
Model verification with independent data	no	no	no	no	no	no
Prediction errors estimable	potentially	potentially	potentially	no	potentially	potentially

variations suggests a potential strategy for the development of climatic predictions over the long time scale (Saltzman, 1984). In particular, any prediction scheme for that time scale must necessarily have two parts. The first part consists of models of slowly varying components of the climate system that generate the temporal evolution of those components. The second part consists of models of fast-response components of the system that generate spatial details of a predicted climate that is in equilibrium with the boundary conditions and slowly varying components. Although the elements of such an overall strategy are individually available--as evidenced by their application to the analysis of past climatic variations--their integration into a general scheme for future variations has yet to be accomplished.

Prediction of Slowly Varying Components. As indicated in the reviews above, a variety of specific models can be used to predict variations of such slowly varying components of the climate system as the ice sheets and deep-ocean temperatures. While such models are currently not well developed, their ability to match the observed records over relatively long intervals gives them a certain measure of robustness. Models of the slowly varying components of the climate system require as input the external boundary conditions, and for the case of incoming solar radiation, this may be computed for the future to a high degree of confidence (Berger, 1984).

Several important problems must be overcome before models of the slowly varying components can be integrated into a general prediction scheme. Variations in boundary conditions of the climate system other than the inputs of solar radiation are not well known. Dust loading and CO_2 concentration in the atmosphere are important controls, but their histories and potential predictability are imperfectly known (Bryson and Goodman, 1980; Hammer and others, 1980; Neftel and others, 1982; Shackleton and others, 1983; Kellogg and Schware, 1981). Similarly, the extent of variations in solar output over long time intervals are not known.

The models of the slowly varying components themselves are in need of much elaboration. The models currently generate global or other very large spatial scale averages, and the spatial structure of the variations of such components as the ice sheets are not immediately forthcoming from the models. Methods for disaggregating the output of or adding greater spatial resolution to the models are therefore needed. Much of the work thus far has focused on the ice sheets, leaving the models of the deep ocean relatively underdeveloped (Saltzman, 1985).

The relative contribution of forced vs. free variations of the slowly varying components must also be assessed to determine the ultimate predictability of those components. If free variations are indeed important, then there may be an as-yet unknown, unacceptably low upper limit to predictability of the slowly varying components.

Prediction of Fast-Response Components. Models of fast-response components of the climate system are needed to resolve the spatial details of the equilibrium climate that would prevail under a particular state of the boundary conditions and slowly varying components. Such models are currently available among the family of GCMs and related models. Those models would be used to generate a snapshot of a climate that could be considered to be physically consistent with a particular set of controls. As for the slowly varying components, basic models of the fast-response components are available, but further elaboration of them is necessary before an operational prediction scheme could be developed.

Models incorporating realistic circulation mechanisms and thermal characteristics of the oceans are still in the developmental stage. These could be important in disaggregating a global-scale prediction of ocean temperature, say, into the proper spatial scale of input required for the initialization of a GCM. Although the character of the ocean surface can be reasonably well specified for the present climate, or for selected times in the past (e.g., 18,000 years B.P., CLIMAP Project Members, 1981), such prescription of ocean conditions cannot currently be made in a satisfactory fashion for predicted future climates. A truly interactive Atmosphere-Ocean GCM (AOGCM) that could be applied in a routine fashion would help bridge the gap between the primarily global-scale output of models of the slowly varying components and the spatially disaggregated data required as input for models of the fast-response components.

Predictions of global ice volume must be spatially disaggregated to the grid-point resolution of the models of the fast-response components. Three-dimensional models of glacial dynamics exist (Denton and Hughes, 1981), and these, along with guidance from the geological record on typical ice-sheet morphology, could be used to supply the needed information.

While GCMs are capable of revealing the spatial detail of a particular equilibrium climate, that detail may still be too coarse for the site-specific predictions that may be required. It should be possible, however, to use the output from a GCM to initialize mesoscale models (e.g., Pielke, 1984) with finer spatial resolution.

Implementation of a Prediction Strategy

Many of the necessary elements are already available for implementing this essentially hierarchical strategy for predicting local climate at the long time scale ($>10^3$ years). Further consideration must be given, however, to the selection of individual models for use in an operational method and to the validation of these models.

Model Selection. Little guidance exists for selecting the best of several models for predicting a particular component of the climate system. This situation arises mainly because the focus of paleoclimatic modeling and analysis has been on understanding and explaining past variations, and only recently has attention been directed toward climate prediction. As a result, a somewhat heterogeneous collection of individual data analyses and models has been assembled, each focusing on a specific aspect of the overall problem of explaining past climates. Because prediction has not been an issue, particular aspects of the performance of a model (such as an estimate of the variance of its prediction errors) have not received the same attention they have in the development of models for daily weather forecasting. Also, little thought has been given to the possible integration of individual models into an overall prediction scheme.

Some existing models are likely candidates for inclusion in a prediction scheme, although because no integration attempt has yet been made, too little is known to either select with assurance or discount completely any particular model. A typical configuration of models might consist of Imbrie and Imbrie's (1980) and Saltzman and Sutura's (1984) models to predict the long-term variations of global ice volume and ocean temperature, the NCAR Community Climate Model (e.g., Kutzbach and Street-Perrott, 1985) to provide snapshots of the fast-response components of the climate system, and a mesoscale meteorological model (Pielke, 1984) to provide sufficient spatial resolution of the resulting configurations. As will be discussed further below, specific models or prediction methods do not exist for all components of the climate system, and until their performance is actually measured, there is no reason to presume this particular group of models is optimal in any way.

A task that may prove as important as the continued refinement of existing models is the articulation of the overall objectives of climate prediction on the long time scale. From this information, the general form of an overall strategy could be developed, and the selection and refinement of specific models can be directed toward implementing this strategy.

Model Validation. An important consideration in comparing models is their relative performance (Schlesinger, 1984). A standard benchmark used is how well a model fits the data with which it is calibrated, or how well it reproduces a particular feature of the paleoclimatic record. In the case of climatic prediction, the issue is how well a model will perform given substantially different input than that with which it was calibrated. In essence, most models have been designed with reference to only a single climatic state (the present "modern climate") or to a single series (for example, the observed ^{18}O record). The danger will always exist, even in the case of a model with elaborate physics, that it will be tuned to work well with the modern climate, possibly at the expense of its overall performance through time.

The appropriate way to measure the performance of climate models, then, is to verify their ability to simulate climates different from today's. The paleoclimatic record is the obvious provider of such alternative climates (Gates, 1976a; Manabe and Hahn, 1977). The way model validation would work in practice is that the boundary conditions and state of the slowly varying components would be input to the hierarchy of prediction models to simulate the climate of a particular time, say, the full-glacial climate of 18,000 years B.P. (e.g., CLIMAP Project Members, 1976). The simulated full-glacial climate would then be compared to the observed climate as interpreted from paleoclimatic evidence (Peterson and others, 1979).

There have been a number of promising exercises in model verification (e.g., Hansen and others, 1984; Manabe and Broccoli, 1985; Kutzbach and Street-Perrott, 1985), but no systematic program of validation has yet been carried out. One necessary element of a systematic program would be the development of a comprehensive paleoclimatic data base, like that being developed for selected dates during the past 18,000 years by COHMAP members (Figure 3-9; Webb and others, 1985; Webb, 1985).

Summary. The overall structure of a climate-prediction scheme for the long time scale (>10^3 years) must include

1. methods for predicting future variations of the boundary conditions and external controls of the climate system;

2. methods for predicting the slowly varying components of the climate system;

3. methods for predicting the fast-response components of the climate system from the state of the boundary conditions and slowly varying components;

4. methods for spatially and temporally disaggregating the fast-response components at the appropriate scale; and

5. methods for assessing the impact of variations of climate on other environmental systems, such as the hydrologic system.

Implementation of the scheme will require iterative definition of the nature of the prediction objectives, selection of candidate models (including the development of new models), and assessment of the performance of the models (model validation).

Availability of Data Bases for Climate Prediction

Three general data sets are needed for the development of a climate-prediction scheme for the long time scale. The first set consists of the past records of the boundary conditions and slowly varying components of the climate system. These records include the input of solar radiation to the climate system, the ice-sheet volume and extent, the horizontal and vertical temperature structure of the oceans, CO_2 concentration, dust loading, and so on. These data are required for the development and testing of prediction methods for the slowly varying components of the climate system.

The second data set consists of comprehensive data on the spatial variability of the present climate. These data are required to initialize models of fast-response components of the climate system. Included in this data set are grid-point values of the standard meteorological variables, as well as data such as sea surface temperature, land surface albedo, surface roughness, soil characteristics, and so on.

To the extent that models of both slowly varying and fast-response components of the climate system have been developed, the basic data included in the first two sets could be said to already exist. As indicated earlier,

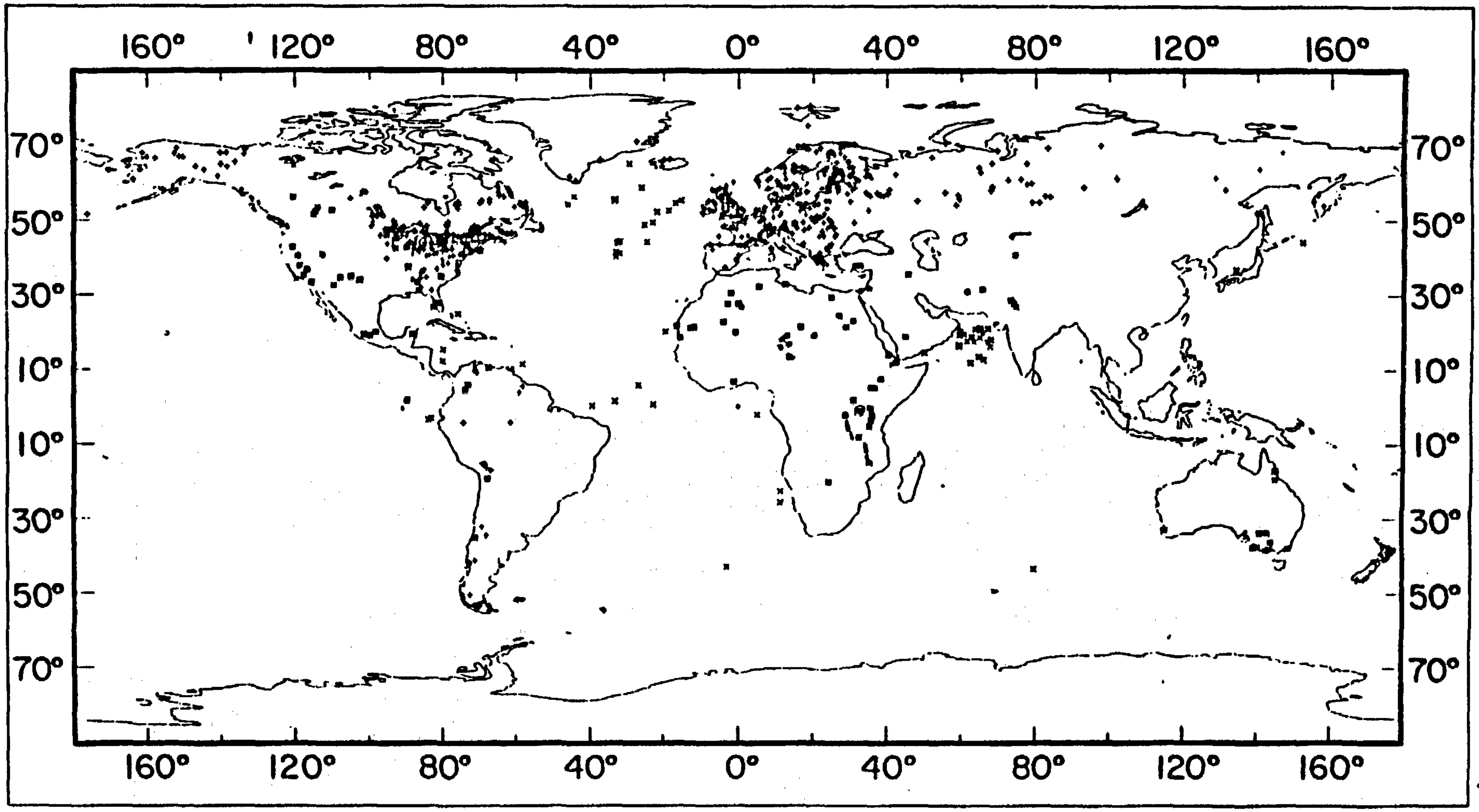


Figure 3-9. Global paleoclimatic data base for 6000 years B.P. (Webb, 1985, Figure 1). Plusses indicate sites with pollen data; asterisks indicate sites with lake-level data; and x's indicate sites with marine plankton data.

models of the slowly varying components presently do not provide much spatial resolution, and further development of the first data set may therefore be required.

The third data set consists of the data necessary for validation of model simulations. The scope of the data that could potentially be included in this set is quite large, including virtually any kind of paleoclimatic evidence.

The set of all paleoclimatic data is enormous and varies greatly in spatial and temporal coverage and in its sensitivity to paleoclimatic variations (Bradley, 1985; Hecht, 1985). Comprehensive data sets for specific times in the past are needed for model validation studies. Methods are also needed for quantitatively comparing the paleoclimatic evidence with the model simulations. While development of a global-scale data base for the past 18,000 years (Webb and others, 1985; Webb, 1985) has begun, much work is still needed to increase the spatial resolution of the data and to develop procedures for data--model comparisons.

Phenomena Not Currently Predictable

As indicated above, specific attempts at climate prediction are few in number, and at present only the global ice volume could be said to be predictable as a function of orbital variations (but not necessarily as a function of anthropogenic CO_2 or dust). With some development, however, the list of potentially predictable features can be expanded. Several areas will need greater development. The climate system itself does not permit the intrinsic identification of events that should be predicted; the desired predictions must be identified from the specific objectives of a prediction exercise. The specific climatic variables targeted for prediction are likely to be regional or local in scale. Models of the fast-response components, including the higher-spatial-resolution mesoscale models, will play an important role in those situations. At present, a complete hierarchy of models, from those of the slowly varying components of the climate system to high-resolution models of the fast-response components, has never been implemented.

Within each class of models, several areas are underdeveloped. In the case of models of the slowly varying components, the main underdeveloped areas include the oceans, in general, and aspects of the ice sheets other than their volume. The oceans are also an underdeveloped element of models of the fast-response components, as are surface energy and water balances (Meehl, 1984).

In a strict sense, therefore, only global ice volume could be considered to be a predictable phenomenon at the long time scale. In a more general sense, although more model development is clearly required, prediction of a fairly comprehensive set of components of the climate system may currently be feasible. Predicted sequences of climatic variables could in turn be used to derive statements of the probability of observing specific climatic changes.

Climate Prediction Performance Assessment

The most appropriate measure of the relative performance of an overall climate prediction strategy would be its success in correctly predicting observed paleoclimates. In addition to facilitating the selection of individual models from the range of those available for the different components of the climate system, a model validation program would enable the value of the overall strategy to be assessed.

There are two specific aspects of the performance of an overall prediction strategy that should be assessed; not surprisingly, these correspond to the slowly varying and fast-response components of the climate system. The performance of any climate prediction strategy must be examined for its ability to correctly reconstruct both the temporal features of the paleoclimatic record (driven mainly by variations of the boundary conditions and slowly varying components) and the spatial features (determined largely by the fast-response components).

Two kinds of validation experiment, each with its own set of data, can thus be envisioned. The first experiment would focus on the performance of models of the slowly varying components and would require the collection of long, continuous records of paleoclimate in key regions. The second experiment would focus on the performance of models of the fast-response components and would require the collection of paleoclimatic records with good spatial coverage for key times. As indicated above, techniques must be developed for translating the climatic output of models into variables directly comparable to the paleoclimatic record. For both experiments, it will be necessary to devise formal procedures for comparing the data with the model output.

Discussion of Currently Available Approaches

At present, no operational method exists for climate prediction at the long time scale (10^3 to 10^4 years, and longer). Many of the necessary components of an overall strategy exist, however, including a variety of models, methods for transforming predictions into probabilistic statements, and the basic data required for model validation. A program is required for adapting exiting data and methods and integrating them into a general method of long-term climate prediction. To guide the development of such a program, we therefore recommend the following:

1. The overall goals of an effort to predict climate variations over the long time scale (10^3 years and greater) should be clearly identified by the potential users of those predictions. Identifying specific objectives of climate prediction will aid development of an overall scheme by revealing where gaps exist. In addition, the influence of climatic variations on the surface-water system, and in turn, on the ground-water system should be reviewed to further refine these objectives.

2. A comprehensive research program should be initiated to adapt existing and develop new methods of climate prediction. Individual tasks in such a program should include the development of methods for

   - predicting the boundary conditions and external controls of the climate system;
   - predicting the slowly varying components of the climate system;
   - predicting the fast-response components of the climate system;
   - developing site-specific predictions of important climatic variables, and
   - assessing the influence of climatic variations on other environmental systems.

   For each of these tasks, model validation studies are required, which should include the development of the appropriate paleoclimatic data bases and the methods for comparing model simulations with paleoclimatic observations. It is likely that such a comprehensive program would require the effort of five or more investigators over a span of five years for completion.

3. Finally, the scientific basis of climate prediction should be periodically reviewed, as new understandings of the causes of climatic variations develop and as new targets for prediction arise.

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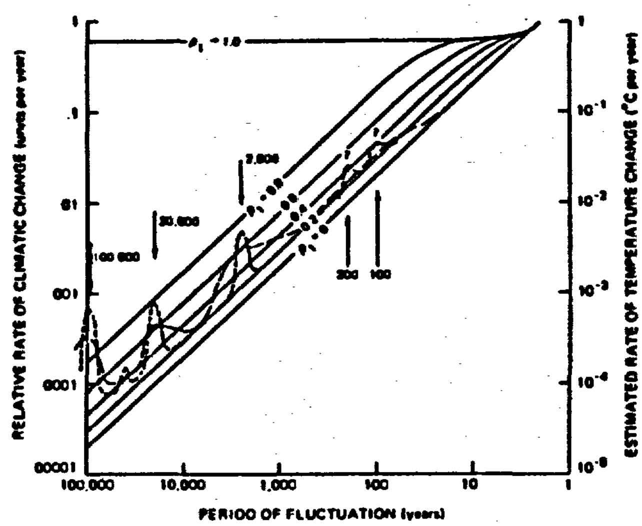
Appendix 3.1

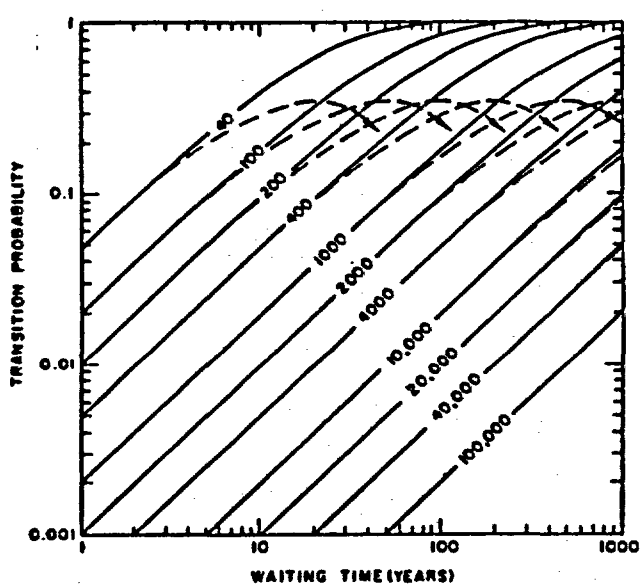
United States Committee for the Global Atmospheric Research Program (1975)

As part of its general review of the nature of climatic variations (Understanding Climatic Change), the US Committee for the Global Atmospheric Research Program (1975) demonstrated how statements of a probabilistic nature could be made about climatic changes. While the paleoclimatic evidence on which the demonstration was based is now somewhat dated, and the assumptions that underlie the methods were not fully tested, the demonstration is still illustrative.

Figure 3-10a portrays the relationship between the rate of climatic change (e.g., of global temperature) and the length of the period over which the change occurs. The vertical axis gives the rate of change expressed as arbitrary units (left-hand axis), or as change in hemispheric average



a. Rates of change of climate attributed to variations of different periods.



b. Probability of the onset of climatic changes as a function of "waiting time."

Figure 3-10. Relative rate of climatic change and transition probability (US Committee for the Global Atmospheric Research Program, 1975, Figures A.30 and A.31).

temperature (right-hand axis). The horizontal axis gives the period. The family of curves (light solid lines) displays the relationship between the period of fluctuation and maximum rate of change that occurs over that period. The curves were derived by assuming that climatic variations are describable by a first-order autoregressive or "red noise" time series model (Gilman and others, 1963). Under such a model, variations in climate are viewed as being generated by simple persistence, coupled with random perturbations of the system (Box and Jenkins, 1976).

Each of the lines in the family of curves was drawn by determining the relative contribution to the total variance of climate by variations at each period. Such information is provided by the variance spectrum of a time series (Priestly, 1981). For a series that can be described by a first-order autoregressive model, the variance spectrum is (Box and Jenkins, 1976, Eq. 3.2.15)

$$g(f) = \frac{2\sigma^2}{1 + \rho^2 - 2\rho\cos(2\pi f)}$$

where

σ^2 = the standard deviation of the series,

ρ = the lag-one autocorrelation coefficient,

f = the frequency of the variation (1/period),

g(f) = the spectral density at frequency f.

The rate of climatic change associated with the variation at each frequency is simply calculated as the product f•g(f) (i.e., the variance divided by period over which it occurs). For example, if $\rho = 0.0$, g(f) = 2, and so variations with a frequency of 1/1000 cycles/yr give rise to a climatic change of 0.002 units/yr. The family of curves was drawn in this fashion for different values of ρ and f.

The dashed line in Figure 3-10a was determined from the variance spectrum of the observed climatic record (see Kutzbach and Bryson, 1974). For periods of less than 200 years, the observed climate record does not depart significantly from random variation (i.e., the curve for $\rho = 0$). For longer periods, the observed climate record resembles one that is non-random, with the variance concentrated at specific periods (i.e., 2500, 20,000, and 100,000 years). At periods of 100,000 years, the observed record is significantly different from one generated by a red-noise process. The implication of this pattern is that over short time intervals, climatic variation is essentially random; at the glacial--interglacial time scale (100,000 years), it is essentially periodic; and at intermediate periods, is describable as a red-noise-like process. The dotted line in the figure was derived by assuming that the observed variations of climate were all quasi-periodic in nature.

As an example of interpreting Figure 3-10a, the arrow labeled "100,000" points to the large variation associated with the glacial--interglacial cycle.

Associated with this 100,000-year periodicity is a rate of change of climate possibly as high as 0.0008 units/yr (relative units for a particular component of the climate system, e.g., the extent of the ice sheets) and a rate of temperature change approaching 10^{-3}°C/yr. Because the rates of change associated with the 100,000-year period are very small on an annual basis, they have little impact on short-term climate variations.

Figure 3-10b portrays the probability of observing a particular kind of climatic change as a function of waiting time, or the time elapsed since the present. The climatic change considered here is one equivalent in magnitude to the transition between the maximum and minimum values of a climatic series. In a periodic series, for example, two transitions of this magnitude occur during a simgle oscillation. An assumption is made that the transitions between the maximum and minimum (or vice versa) are random events, which is clearly not the case for a periodic series. Under that assumption, the probability of one or more transitions occurring during a particular interval is given by the Poisson distribution (Priestley, 1981, Eq. 2.11.3)

$$p(i) = \frac{(\lambda t)^i}{i!} e^{-\lambda t}$$

where p(i) is the probability of realizing i transitions during time interval t, given that the <u>mean</u> rate of occurrence of transitions over the interval is λ.

Consider, for example, the line labeled 10,000 in Figure 3-10b. The mean rate of occurrence of climatic transitions for this period of variation is $\lambda = 2(1/10{,}000)$, because two transitions are possible, on average, over one cycle of this duration. Using the above equation, the probability of observing one transition during the next 1000 years, equivalent in magnitude to the kind of variations that occur over a period of 10,000 years, is

$$p(1) = 0.2e^{-0.2}$$

$$= 0.16$$

The probability of n such transitions is

$$p(n) = 0.2e^{-0.2} \sum_{i=1}^{n} \frac{.2^i}{i!}$$

$$= 0.2e^{-0.2} + 0.2e^{-0.2}\frac{.2^2}{2} + 0.2e^{-0.2}\frac{.2^3}{6}$$

$$+ \ldots + 0.2e^{-0.2}\frac{.2^n}{n!}$$

$$= .16 + .02 + .001 + \ldots$$

$$\simeq 0.18.$$

Repeated application of this procedure gives the family of curves in Figure 3-10b. For waiting periods equal to the period of fluctuation of a series, the probability of observing exactly one climatic transition is 0.27, indicated in the figure by the arrows.

Appendix 3.2

Imbrie and Imbrie (1980)

Introduction

The relative simplicity of inductive climate models stands in sharp contrast to all other classes of models. Inductive models are physically based but mathematically simple, and their simulated results can be easily compared to geologic records. This approach involves establishing and tuning a mathematical model to produce a time series of values approximating a known record for an indirect climate indicator, e.g., the ^{18}O isotope record from deep sea cores. Imbrie and Imbrie (1980) have developed a remarkably uncomplicated model, unsurpassed in its ability to simulate a particular paleoclimate record, that is representative of inductive climate modeling.

Models of this type, based on Milankovitch or astronomical climate theory, simulate the past climate record by modeling effects of variations in solar irradiation brought about by long-term changes in Earth-Sun geometry. These orbital elements--eccentricity (e), precession (n), and obliquity (w)--are nearly periodic functions with periods of roughly 100,000, 41,000, and 22,000 years respectively. Recent research using spectral analysis of climate records for the past 730,000 years has enabled confirmation that, in the past, the climatic system has responded to variations in solar forcing associated with obliquity and precession (Hays and others, 1976). In light of this evidence, Imbrie and Imbrie (1980) argued for a shift in strategy of climate research, away from searching for evidence of the astronomical theory to using past geologic records for evaluating performance of models based on the theory. Further, they offered insight on the role the 100,000-year cycle in eccentricity plays in climate change.

Imbrie and Imbrie (1980) discussed equilibrium and differential models. Differential models are somewhat more complicated physically and mathematically, but both are relatively simple compared with GCMs and SDMs.

Equilibrium models were the first inductive models to be used. Mathematically, they can be written $y = f(x)$; where y is an equilibrium climate state determined as a function of the orbital boundary condition vector, $x = x(e,n,w)$. Solving the system equation through time eventually yields a simulated climate in equilibrium with the fixed orbital parameter vector x. Results of running these models to reproduce past climatic fluctuations have met with varying levels of success, the major shortcoming being the time lag between the actual geologic record and modeled output.

Differential models are based on time-dependent characteristics of the climate system. The general form of these models is $dy/dt = f(x,y)$; where, as before, f is a system function relating the orbital boundary conditions vector x to the state of the climate system y. Differential models are more realistic than equilibrium models because they simulate the climate system's dynamic response to changing boundary conditions, and eliminate time lag problems exhibited by equilibrium models.

Model Description

Imbrie and Imbrie's (1980) model simulates changes in global ice volume. Their decision to develop such a model was based on the quality and length of oxygen isotope records for comparison to model output and on knowledge that cryospheric response to climatic variations is temporally similar in scale to orbital forcing (Hays and others, 1976).

Under the assumption that there is sufficient evidence to indicate that ice sheets shrink at a faster rate than they grow, Imbrie and Imbrie (1980) formulated their nonlinear model as $dy/dt = (1/T_i)(x-y)$; where T_i is a time constant taking one of two values depending on whether the climate is warming up or cooling down. The system function, $f(x,y) = (1/T_i)(x-y)$, reflects both realistic physical principles and the nature of the observed climate record and allows the model to be tuned to the record.

Results

Input to the model was a periodic function corresponding to a July irradiation curve for 65°N latitude. The output was compared to oxygen isotope curves obtained from two deep sea cores--RC11-120 from the southern Indian Ocean, and V28-238 from the Pacific Ocean (Figure 3-9). Included in the output is a prediction that long-term cooling, which started about 6,000 years ago, will continue for the next 23,000 years. This prediction is based only on continued periodic variations in solar forcing and does not account for other possible sources of variation.

The model output correlates well with the climate record over the past 100,000 years, but shows diminishing correlation up to 350,000 years. Beyond 350,000 years, the output departs from the climate record significantly. Over the 500,000-year time scale, Imbrie and Imbrie (1980) stated that their model fails to perfectly simulate a time series with expected spectral power at 413,000, 100,000, 23,000, and 19,000 years. They attributed some of this apparent error to characteristics of the input and, further, speculated on the possibility that significant output errors could be the result of almost intransitive responses of the climate system.

Imbrie and Imbrie's (1980) model reproduced the climate record with good agreement; they expressed uncertainty over the reason for strong 100,000-year oscillations evident in both the climate record and model output, however. In a recent analysis of Imbrie and Imbrie's model, Snieder (1985) was able to determine the source of the 100,000-year cycle, lending further support to the physical basis for this modeling method.

Imbrie and Imbrie (1980) ran their model using a heating function with forcing frequencies of 19,000, 23,000, and 41,000 years. Snieder (1985), however, modified the model by using a different heating function. His function was a linear combination of simple harmonic equations of two frequencies. This form of heating function produced amplitude modulation, a form of interference that occurs when two frequencies are added or combined. (Amplitude modulation can cause fourfold increases in combined power.)

Using spectral analysis, Snieder (1985) found that his modified model yielded output with a strong spectral component (power) at at third frequency. He discovered through a series of experiments that, by using forcing frequencies of 19,000 and 23,000 years, the power spectrum showed a very strong signal at 109,000 years. This agreed with results reported by Hays and others (1976) concerning the nature of the 23,000-year cycle in precession. The combined effects of precession and eccentricity (100,000-year cycle) resulted in splitting the 23,000-year cycle into an additional component with a frequency of 19,000 years. Snieder (1985) was thus able to attribute power at 109,000 years to conversion of amplitude modulation (derived from interference between the 19,000 and 23,000 cycles) by Imbrie and Imbrie's nonlinear model. Snieder (1985) concluded that the nearly 100,000-year cycle is due to combined external variations in solar forcing rather than internal resonance in the climatic system.

References

Adem, J., A. Berger, Ph. Gaspar, P. Pestiaux, and J. P. van Ypersele, 1984, "Preliminary Results on the Simulation of the Climate During the Last Deglaciation with a Thermodynamic Model," in A. Berger, J. Imbrie, J. Hays, G. Kukla, and B. Saltzman, eds., Milankovitch and Climate--Understanding the Response to Astronomical Forcing, Part 2, D. Reidel Co., Dordrecht, Holland, p. 527-537.

Benson, L. V., 1981, "Paleoclimatic Significance of Lake-Level Fluctuations in the Lahontan Basin," Quaternary Research, vol. 16, p. 390-403.

Berger, A., 1977, "Power and Limitation of an Energy-Balance Climate Model Applied to the Astronomical Theory of Paleoclimates," Paleogeography, Paleoclimatology, Paleoecology, vol. 21, p. 3-39.

Berger, A., 1984, "Accuracy and Frequency Stability of the Earth's Orbital Elements During the Quaternary," in A. Berger, J. Imbrie, J. Hays, G. Kukla, and B. Saltzman, eds., Milankovitch and Climate--Understanding the Response to Astronomical Forcing, Part 2, D. Reidel Co., Dordrecht, Holland, p. 3-39.

Berger, A., J. Imbrie, J. Hays, G. Kukla, and B. Saltzman, eds., 1984, Milankovitch and Climate--Understanding the Response to Astronomical Forcing, D. Reidel Co., Dordrecht, Holland.

Box, George E. P., and Gwilym M. Jenkins, 1976, Time Series Analysis--Forecasting and Control, Holden-Day, San Francisco, 575 pp.

Bradley, R. S., 1985, Quaternary Paleoclimatology: Methods of Paleoclimatic Reconstruction, Allen and Unwin, Boston, 472 pp.

Bredehoeft, J. D., W. Back, and B. B. Hanshaw, 1982, "Regional Ground-Water Flow Concepts in the United States: Historical Perspective," in T. N. Narasimhan, ed., Recent Trends in Hydrogeology, Special Paper 189, Geol. Soc. Amer., 448 pp.

Bryson, Reid A., and Brian M. Goodman, 1980, "Volcanic Activity and Climatic Changes," Science, vol. 207, p. 1041-1044.

Budyko, M. I., 1982, The Earth's Climate: Past and Future, Academic Press, New York, 307 pp.

CLIMAP Project Members, 1976, "The Surface of the Ice-Age Earth," Science, vol. 191, p. 1131-1137.

CLIMAP Project Members, 1981, "Seasonal Reconstructions of the Earth's Surface at the Last Glacial Maximum," Geol. Soc. Amer. Map and Chart Series, MC-36, p. 1-18.

Committee on the Atmospheric Effects of Nuclear Explosions, 1985, The Effects on the Atmosphere of a Major Nuclear Exchange, National Academy Press, Washington, DC, 193 pp.

Denton, G. H., and T. J. Hughes, eds., 1981, The Last Great Ice Sheets, Wiley-Interscience, New York, 484 pp.

Gates, W. L., 1976a, "The Numerical Simulation of Ice-Age Climate with a Global General Circulation Model," Jour. Atmospheric Sci., vol. 33, p. 1844-1873.

Gates, W. L., 1976b, "Modeling the Ice-Age Climate," Science, vol. 191, p. 1138-1144.

Gates, W. L., 1981, "The Climate System and Its Portrayal by Climate Models: A Review of Basic Principals. I. Physical Basis for Climate," in A. Berger, ed., Climatic Variations and Variability: Facts and Theories, D. Reidel Co., Dordrecht, Holland, p. 3-20.

Ghil, M., 1981, "Internal Climatic Mechanisms Participating in Glaciation Cycles," in A. Berger, ed., Climate Variations and Variability: Facts and Theories, D. Reidel, Dordrecht, Holland, p. 461-480.

Gilman, D. L., F. J. Fulgister, and J. M. Mitchell, Jr., 1963, "On the Power Spectrum of 'Red Noise,'" Jour. Atmospheric Sci., vol. 20, p. 182-184.

Goudie, Andrew, 1983, Environmental Change, 2nd ed., Oxford University Press, Oxford, 258 pp.

Hammer, C. U., H. B. Clausen, and W. Dansgaard, 1980, "Greenland Ice Sheet Evidence of Post-Glacial Volcanism and Its Climatic Impact," Nature, vol. 288, p. 239.

Hansen, J., A. Lacis, D. Rind, G. Russell, I. Fung, R. Rudey, and J. Lerner, 1984, "Climate Sensitivity: Analysis of Feedback Mechanisms," in James E. Hansen and Taro Takahashi, eds., Climate Processes and Climate Sensitivity, Geophysical Monograph 29, Amer. Geophys. Union, p. 130-163.

Hays, J. D., J. Imbrie, and N. J. Shackleton, 1976, "Variations in the Earth's Orbit: Pacemaker of the Ice Ages," Science, vol. 194, p. 1121-1132.

Heathcote, R. L., 1983, The Arid Lands: Their Use and Abuse, Longman, New York, 321 pp.

Hecht, Alan D., 1985, "Paleoclimatology: A Retrospective of the Past 20 Years," in A. D. Hecht, ed., Paleoclimate Analysis and Modelling, J. Wiley and Sons, Inc., New York, p. 1-25.

Imbrie, John, 1985, "The Future of Paleoclimatology," in A. D. Hecht, ed., Paleoclimate Analysis and Modelling, J. Wiley and Sons, Inc., New York, p. 423-432.

Imbrie, John, and John Z. Imbrie, 1980, "Modeling the Climatic Response to Orbital Variations," Science, vol. 207, p. 943-953.

Kanari, S., N. Fuji, and S. Horie, 1984, "The Paleo-Climatological Constituents of Paleotemperature in Lake Biwa," in A. Berger, J. Imbrie, J. Hays, G. Kukla, and B. Saltzman, eds., Milankovitch and Climate--Understanding the Response to Astronomical Forcing, Part 1, D. Reidel Co., Dordrecht, Holland, p. 405-414.

Kellogg, William W., and Robert Schware, 1981, Climate Change and Society: Consequences of Increasing Atmospheric Carbon Dioxide, Westview Press, Boulder, CO, 172 pp.

Kominz, Michelle A., and Nicklas G. Pisias, 1979, "Pleistocene Climate: Deterministic or Stochastic," Science, vol. 204, p. 171-173.

Kukla, G. J., and R. K. Matthews, 1972, "When Will the Present Interglacial End?," Science, vol. 178, p. 190-191.

Kukla, G., A. Berger, R. Lotti, and J. Brown, 1981, "Orbital Signature of the Interglacials," Nature, vol. 290, p. 295-300.

Kutzbach, J. E., 1976, "The Nature of Climate and Climatic Variations," Quaternary Research, vol. 6, p. 471-480.

Kutzbach, John E., 1980, "Estimates of Past Climate at Paleolake Chad, North Africa, Based on a Hydrological and Energy-Balance Model," Quaternary Research, vol. 14, p. 210-223.

Kutzbach, J. E., 1981, "Monsoon Climate of the Early Holocene: Climate Experiment with the Earth's Orbital Parameters for 9000 Years Ago," Science, vol. 214, p. 59-61.

Kutzbach, J. E., and R. A. Bryson, 1974, "Variance Spectrum of Holocene Climate Fluctuations in the North Atlantic Sector," Jour. Atmospheric Sci., vol. 31, p. 1958-1962.

Kutzbach, J. E., and P. J. Guetter, 1984, "The Sensitivity of Monsoon Climates to Orbital Parameter Changes for 9,000 Years BP: Experiments with the NCAR General Circulation Model," in A. Berger, J. Imbrie, J. Hays, G. Kukla, and B. Saltzman, eds., Milankovitch and Climate--Understanding the Response to Astronomical Forcing, Part 2, D. Reidel Co., Dordrecht, Holland, p. 801-802.

Kutzbach, J. E., and B. L. Otto-Bliesner, 1982, "The Sensitivity of the African-Asian Monsoon to Orbital Parameter Changes 9000 Years BP in a Low-Resolution General Circulation Model," Jour. Atmospheric Sci., vol. 39, p. 1177-1188.

Kutzbach, John E., and F. Alayne Street-Perrott, 1985, "Milankovitch Forcing of Fluctuations in the Level of Tropical Lakes from 18 to 0 Kyr BP," Nature, vol. 317, p. 130-134.

Lamb, H. H., 1982, Climate, History and the Modern World, Methuen and Co. Ltd., London, 387 pp.

Manabe, S., and A. J. Broccoli, 1985, "The Influence of Continental Ice Sheets on the Climate of an Ice Age," Jour. Geophys. Research, vol. 90, p. 2167-2190.

Manabe, Syukuro, and Douglas G. Hahn, 1977, "Simulation of the Tropical Climate of an Ice Age," Jour. Geophys. Research, vol. 82, p. 3889-3911.

Meehl, Gerald A., 1984, "Modeling of the Earth's Climate," Climatic Change, vol. 6, p. 259-286.

Mitchell, J. Murray, Jr., 1976, "An Overview of Climatic Variability and Its Causal Mechanisms," Quaternary Research, vol. 6, p. 481-493.

Namias, J., 1975, Short Period Climatic Variations, University of California, San Diego, 905 pp.

Neftel, A., H. Oeschger, J. Schwander, B. Stauffer, and R. Zumbrunn, 1982, "Ice Core Sample Measurements Give Atmospheric CO_2 Content During the Past 40,000 Yr," Nature, vol. 295, p. 220-223.

North, Gerald R., Robert F. Cahalan, and James A. Coakley, Jr., 1981, "Energy Balance Climate Models," Rev. Geophys. Space Phys., vol. 19, p. 91-121.

North, G. R., J. G. Mengel, and D. A. Short, 1984, "A Two-Dimensional Climate Model Useful in Ice Age Applications," in A. Berger, J. Imbrie, J. Hays, G. Kukla, and B. Saltzman, eds., Milankovitch and Climate--Understanding the Response to Astronomical Forcing, Part 2, D. Reidel Co., Dordrecht, Holland, p. 513-518.

Oerlemans, J., 1982, "Glacial Cycles and Ice-Sheet Modelling," Climatic Change, vol. 4, p. 353-374.

Oerlemans, J., 1984, "On the Origin of the Ice Ages," in A. Berger, J. Imbrie, J. Hays, G. Kukla, and B. Saltzman, eds., Milankovitch and Climate--Understanding the Response to Astronomical Forcing, Part 2, D. Reidel Co., Dordrecht, Holland, p. 607-611.

Petersen, Erik Lundtang, and Søren E. Larsen, 1978, "A Statistical Study of a Composite Isotopic Paleotemperature Series From the Last 700,000 Years," Tellus, vol. 30, p. 193-200.

Peterson, G. M., T. Webb III, J. E. Kutzbach, T. van der Hammen, T. Wijmstra, and F. A. Street, 1979, "The Continental Record of Environmental Conditions at 18,000 Yr B.P.: An Initial Evaluation," Quaternary Research, vol. 12, p. 47-82.

Pielke, Roger A., 1984, Mesoscale Meteorological Modeling, Academic Press, Orlando, 612 pp.

Pisias, N. G., and T. C. Moore, Jr., 1981, "The Evolution of Pleistocene Climate: A Time Series Approach," Earth and Planet Sci. Let., vol. 52, p. 450-458.

Pollard, David, 1983, "Ice-Age Simulations with a Calving Ice-Sheet Model," Quaternary Research, vol. 20, p. 30-48.

Priestley, M. B., 1981, Spectral Analysis and Time Series, vol. 1, Academic Press, London, 653 pp.

Saltzman, B., 1978, "A Survey of Statistical-Dynamical Models of the Terrestrial Climate," Adv. Geophys., vol. 20, p. 183-304.

Saltzman, B., 1983, "Climatic Systems Analysis," in Barry Saltzman, ed., Theory of Climate, Adv. Geophys., vol. 25, p. 173-233.

Saltzman, Barry, 1984, "On the Role of Equilibrium Atmospheric Climate Models in the Theory of Long-Period Glacial Variations," Jour. Atmospheric Sci., vol. 41, p. 2263-2266.

Saltzman, Barry, 1985, "Paleoclimatic Modeling," in A. D. Hecht, ed., Paleoclimate Analysis and Modelling, J. Wiley and Sons, Inc., New York, p. 341-396.

Saltzman, Barry, and Alfonso Sutera, 1984, "A Model of the Internal Feedback System Involved in Late Quaternary Climatic Variations," Jour. Atmospheric Sci., vol. 41, p. 736-745.

Saltzman, B., A. R. Hansen, and K. Maasch, 1984, "The Late Quaternary Glaciations as a Response of a Three Component Feedback System to Earth-Orbital Forcing," Jour. Atmospheric Sci., vol. 41, p. 3380-3389.

Schlesinger, M. E., 1984, "Climate Model Simulations of CO_2-Induced Climate Change," Adv. Geophys., vol. 26, p. 141-235.

Schneider, Stephen H., 1984, "On the Empirical Verification of Model-Predicted CO_2-Induced Climate Effects," in James E. Hansen and Taro Takahashi, eds., Climate Processes and Climate Sensitivity, Geophysical Monograph 29, p. 187-207.

Sellers, W. D., 1969, "A Climate Model Based on the Energy Balance of the Earth-Atmosphere System," Jour. Appl. Meteorology, vol. 8, p. 392-400.

Shackleton, N. J., and N. G. Pisias, 1985, "Atmospheric Carbon Dioxide, Orbital Forcing, and Climate," in E. T. Sundquist and W. S. Broecker, eds., The Carbon Cycle and Atmospheric CO_2: Natural Variations Archean to Present, Geophysical Monograph 32, Amer. Geophys. Union, p. 303-317.

Shackleton, N. J., M. A. Hall, J. Line, and Cang Shuxi, 1983, "Carbon Isotope Data in Core V19-30 Confirm Reduced Carbon Dioxide Concentration in the Ice Age Atmosphere," Nature, vol. 306, p. 319-322.

Smith, George I., and Alayne Street-Perrott, 1983, "Pluvial Lakes of the Western United States," in H. E. Wright, Jr., and Stephen C. Porter, eds., Late-Quaternary Environments of the United States, Volume 1, The Late Pleistocene, Univ. of Minnesota Press, Minneapolis, MN, 407 pp.

Snieder, Roelof K., 1985, "The Origin of the 100,000 Year Cycle in a Simple Ice Age Model," Jour. Geophys. Research, vol. 90, p. 5661-5664.

Street-Perrott, F. Alayne, and Sandra P. Harrison, 1984, "Temporal Variations in Lake Levels Since 30,000 YR BP--An Index of the Global Hydrological Cycle," in James E. Hansen and Taro Takahashi, eds., Climate Processes and Climatic Sensitivity, Geophysical Monograph 29, Amer. Geophys. Union, p. 118-129.

Street-Perrott, Alayne, Max Beran, and Robert Ratcliffe, 1983, Variations in the Global Water Budget, D. Reidel Co., Dordrecht, 518 pp.

US Committee for the Global Atmospheric Research Program, 1975, Understanding Climate Change--A Program for Action, National Research Council, National Academy of Sciences, Washington, DC, 239 pp.

Webb, Thompson, III, 1985, A Global Paleoclimatic Data Base for 6000 Yr B.P., Rept. DOE/EV/10097-6, TR018, US Department of Energy, Office of Energy Research, Office of Basic Energy Sciences, Carbon Dioxide Research Division, 155 pp.

Webb, Thompson, III, John Kutzbach, and F. Alayne Street-Perrott, 1985, "20,000 Years of Global Climatic Change: Paleoclimatic Research Plan," in T. F. Malone and J. G. Roederer, eds., Global Change, ICSU Press, in press.

Webb, Thompson, III, F. Alayne Street, and Sally Howe, 1979, Precipitation and Lake-Level Changes in the West and Midwest Over the Past 10,000 to 24,000 Years, Report to Lawrence Livermore Laboratory, Livermore, CA, 102 pp.

Williams, Jill, R. G. Barry, and W. M. Washington, 1974, "Simulation of the Atmospheric Circulation Using the NCAR Global Circulation Model with the Ice Age Boundary Conditions," Jour. Atmospheric Sci., vol. 13, p. 305-317.

Winograd, Isaac J., and William Thordarson, 1975, "Hydrogeologic and Hydrochemical Framework, South-Central Great Basin, Nevada--California, With Special Reference to the Nevada Test Site," US Geological Survey Prof. Paper 712-C, 126 pp.

Chapter 4

TECTONICS AND SEISMICITY*

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Abstract

The geology of the repository site is the fundamental source of data for quantitatively evaluating tectonic and seismic hazards that could affect a nuclear-waste repository. Four kinds of geologic data are most useful for predicting potential tectonic activity near a waste repository: surface ruptures along fault zones; stratigraphic sequences related to tectonic activity; landforms related to surface rupture and regional uplift or subsidence; and relationships between seismicity and tectonic features.

Recurrence methods provide the best data set for probabilistic prediction of long-term behavior of a fault zone, but these methods are often severely limited by proper age control. Stratigraphic sequences are probably the best single data source for fault recurrence studies, but only relatively young (late Quaternary or younger) sequences offer significant resolution. Landform analysis, especially fault-scarp morphology, offers potentially significant information, but the precision is low, particularly from regional analysis. In every case, the best data are obtained when there has been late Quaternary or Holocene tectonism and related sedimentation.

Earthquake prediction depends on the availability of long- and short-term precursors, a well-established historical seismic record, and detailed monitoring networks for precursors of all kinds. The greatest weakness of earthquake prediction is the lack of understanding of the fundamental tectonic processes that create the earthquake source, particularly in intraplate settings. The prediction of the maximum magnitude of an earthquake from the relationship between geologic features and seismicity associated with an earthquake source is a corollary problem to the prediction of earthquakes. In both seismic and aseismic areas, prediction of the magnitude of future events is largely based on the qualitative perception of the possible extent of rupture; few quantitative data exist.

A number of high-quality data bases are readily available for the evaluation of tectonic and seismic phenomena, although site-specific studies are few.

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*This chapter reviews and evaluates techniques for assigning probabilities to future tectonic and seismic events. This review and evaluation does not imply that the NRC has endorsed the use of the techniques discussed.

Earthquake hazard analysis in aseismic or weakly seismic regions requires that the process of reactivation of basement structures be understood. If the stress regime acting on a known tectonic feature with predictable failure mechanisms is known, then it may be possible to predict the magnitude and location of the seismic hazard. This approach has yet to be quantitatively tested.

Methods that establish the causes and present state of crustal stress and that characterize the tectonic features of a region offer significant potential for creating more realistic performance assessments. Using the expert judgment of a broad range of earth-science professionals to illuminate these factors, this method can generate a factual matrix of relevant physical characteristics and a statistically quantitative estimate of tectonic/seismic hazard. This method has been broadly tested for the eastern United States.

At present, no tectonic or seismologic method is completely adequate to quantitatively assess, with a high degree of certainty, the probability of tectonic activity at a repository site.

Introduction

Determining the probability of tectonic activity and the probability of impaired repository performance are to some extent separate activities. Techniques for probabilistic prediction of tectonic motion and seismicity are discussed here, and probabilistic prediction of seismic effects on a site is discussed in Chapter 5.

The geology of the repository site is the fundamental source of data for quantitatively evaluating tectonic and seismic hazards that could affect a nuclear-waste repository. Site geology is dependent on processes acting on various scales, including the whole earth (tectonic plates), regional (the tectonic province in which the site resides), and local (the site itself and the geology within a 100-km radius of the site).

In general, quantitative models at the whole-earth scale predict plate movements within millions of years, identify broad areas of Quaternary activity or potential activity, predict variations in plate positions and velocity that may cause major changes in intraplate strain, and generally identify areas of low orogenic or epeirogenic activity (cf. Chapple and Tullis, 1977; Richardson and others, 1979). Identifying areas of low orogenic or epeirogenic activity is presently very imprecise. For example, continental interiors, which are affected by glacial loading in the 10^4- to 10^5-year time span, and intraplate seismic belts, in which the recurrence interval is very long but energy release may be significant (New Madrid, Charleston, Rio Grande rift, and so forth), are typical areas that might be broadly identified without much quantitative prediction allowed by the geologic data.

Regional analyses evaluate broad patterns of faulting, tectonic sedimentation, epeirogenic movements, changes in fluvial and marine regimes, crustal stress environments, and so forth. Defining regional boundaries and obtaining reasonable temporal and stratigraphic precision may be difficult. If regional areas are seismic (macro or micro), classification of tectonic phenomena is reasonably straightforward (EPRI, 1985). However, in aseismic areas--that is, those areas in which historic earthquakes have not been recorded--tectonic provinces are largely determined by basement boundaries, and basement effects are poorly understood and largely unquantified. To adequately define regional geologic-province boundaries for waste-repository studies and to identify potential sources of tectonic hazards, the time scale of relevant deformation must be expanded to include late Tertiary time; the Quaternary time frame is far too narrow.

The most quantitative and precise tectonic data available to predict future behavior at a given site come from local areas that have been active in Holocene or late Quaternary time ($<10^5$ years). Areas of older tectonic activity yield information of significantly less precision ($\pm10^4$ to 10^6 years or more). Thus a basic contradiction arises in waste-repository analysis: active tectonic zones yield the most predictive information, but these areas have a potentially adverse condition as defined by 10 CFR 60.

Four kinds of geologic data are most useful for predicting potential tectonic activity near a waste repository. These are surface ruptures along fault zones, stratigraphic sequences related to tectonic activity, landforms related to surface rupture and regional uplift or subsidence, and relationships between seismicity and tectonic features. As a general rule, as the size and geologic age of the area considered in a specific investigation decrease, the accuracy, precision, and validity of probabilistic estimates increase. (Predicting tectonic activity without surface effects is also briefly discussed below.)

Earthquake prediction and detailed seismic analysis are not extensively discussed in this report, even though the seismic data base plays a critical role in evaluating young tectonic phenomena. For completeness, one section includes a brief review of seismic methods. Note, however, that the short instrumental record and society-dependent historic earthquake record can be an inadequate statistical base for evaluating even late Quaternary tectonic phenomena. For example, it is useful to consider whether earthquake processes are episodic on the scale of 10^5 years (see Allen, 1975). If they are, then seismic analysis based on the historic record may be meaningless in waste-repository performance assessments, and the understanding of the relationship between seismic and tectonic events more tenuous than currently assumed.

This chapter discusses neither geochemical data nor the theoretical basis for the large-scale physical processes that drive whole-earth systems and the resultant regional stress-strain environment. Rather, it summarizes and assesses the major quantitative geomorphic or geologic techniques for estimating tectonic hazards in waste-disposal site evaluation and reviews the empirical relationships between tectonics and seismicity. The basic analytical methods are presented in three categories:

1. Rupture of land surface (paleoseismicity);

2. Recent vertical crustal movements, emphasizing regional tectonic phenomena; and

3. Correlation of tectonics and seismicity.

The basic characteristics of each major method are summarized in five categories:

1. Description and objectives (Methods);
2. Resolution and types of results (Results);
3. Basic assumptions and data requirements (Data);
4. Problems, limitations, and reliability (Limitations); and
5. Strengths, weaknesses, effectiveness, and possibilities (Assessment).

The selected key references cited in the summaries emphasize more recent and more quantitative studies.

Methods

Rupture of Land Surface

Fault Recurrence. Recurrence methods use reasonably well dated Quaternary deposits to infer the number, ages, and style of fault offsets. The ages of the most recent or multiple earlier ruptures are derived from the relationship between the fault trace and Quaternary deposits of known or estimated age.

Method. Recurrence methods examine the presence and amounts of offsets of one or more dated units exposed naturally or artificially by a given fault trace. Most stratigraphic units either postdate or predate a given rupture event (e.g., alluvial fan deposits, sag pond or lacustrine deposits, or river terrace deposits), and thus the ages of the deposits that are and are not faulted by a given rupture bracket its age (Sieh, 1978a; Weldon and Sieh, 1985). Some deposits are inferred to have occurred during the rupture event itself (e.g., colluvial wedges along the buried trace of a fault (Swan and others, 1980)). Some faulted stratigraphic units may be correlated with offset landforms like stream channels or terraces or with topographic fault scarps (Sieh, 1984; Sieh and Jahns, 1984; Weldon and Sieh, 1985; Swan and others, 1980).

Results. Recurrence methods can estimate the age of the most recent rupture and the number and frequency of prior rupture events. The latter data can be converted to estimates of either recurrence intervals or mean slip rates. The resolution varies widely, depending on the quality and availability of accurately dated units; the number of such units relative to faulting events; the repeat time of the fault relative to the age span of the units; and the clarity of geologic relationships between fault and deposits. Repeat times range from 10^2 to $>10^5$ years/event, depending on the fault zone; the precision of slip rates varies accordingly. Slip rates are usually given in mm/yr or mm/10^3 to 10^4 years. Statistical treatment of repeat intervals may be used where a successive series of multiply-offset, dated deposits occurs (Sieh, 1978a; Weldon and Sieh, 1985). Data reduction leads to a probabilistic repeat time, based on past faulting history.

Data. The use of recurrence methods requires a well exposed sequence of deposits and fault; adequate age control of deposits and fault; a clear relationship between dated deposits and fault trace(s), especially with respect to presence or absence of offsets; and a geologic setting suitable for continued deposition and preservation of deposits near the fault trace (e.g., sag pond, aggrading alluvial fan, terrace sequence, antithetic graben fill).

Several basic assumptions are significant in this method. Assumptions about the magnitude of the rupture are especially critical where only vertical exposures are available (cf. Sieh, 1978a, 1978b, 1984)--this problem can be mitigated by examination of lateral offset of landforms, if present. In some cases, relatively uniform repeat times between events are assumed--this is especially critical when uniform slip rates are inferred from a few faulted deposits of drastically different ages. Finally, past fault behavior is assumed to accurately reflect, and even predict, future rupture patterns.

Limitations. There are a number of limitations on the use of this method. Good age control on deposits is frequently lacking. The fault surface may be poorly exposed, or fault behavior may be nonuniform in time and space. Very long recurrence times, relative to the age span of deposits, such as 10^5 years in late Quaternary time, or long repeat times relative to cited slip rates, for example, 10^4 or 10^5 years converted to mm/yr, cast doubt on the real significance of the slip rate. Poor bracketing relationships, such as a long time span between youngest faulted and oldest unfaulted deposits, relative to a given rupture, critically affect the resolution of rupture-age estimates. The presence of relatively few ruptures at given site reduces the statistical data base and hence reliability of any repeat-time projections. The relationship between faults and sedimentary deposits assumed to be related to faulting can be ambiguous. These methods generally are costly, because they require trenching and dating of units.

Assessment. In ideal situations, recurrence methods provide the best data set possible for probabilistic prediction of long-term behavior of a given fault, especially for faults active in Holocene time (Sieh, 1978a, 1978b, 1984; Sieh and Jahns, 1984; Weldon and Sieh, 1985; Swan and others, 1980). Many, if not most, faults lack one or more of the requirements for high-resolution studies of this type, however. The most common problem is poor age control, usually because of a lack of dateable materials (Bonilla and others, 1984; Pearthree and Calvo, 1982; McCalpin, 1982).

Dating Techniques for Quaternary Deposits. The use of recurrence methods requires some means of dating the deposits ruptured by a fault. Various techniques for dating Quaternary deposits are discussed below, in generally decreasing order of reliability and precision. Good general discusssions have been given by Bradley (1985), Goudie (1981), and Colman and Pierce (1979).

Radiometric Dating. Carbon-14 dating is the most common method used for late Quaternary deposits, but it is limited to deposits from certain environments, such as bogs. It is not generally useful in oxidizing environments such as alluvial fan deposits. C-14 dating usually has an upper limit of 30,000 to 50,000 years, although 70,000 to 100,000 years is possible. Relatively large samples are required in the absence of a linear accelerator. Samples are often contaminated, because the carbon system commonly is not closed in nature.

Potassium-argon dating is useful in volcanic rocks, but not in sedimentary deposits. It is generally reliable only in deposits that are older than 50,000 to 100,000 years and younger than 10^6 years. Contamination or excess Ar may be a serious problem in many systems. Precision laboratory techniques are needed to date late Quaternary rocks.

Uranium-series dating uses the relative properties of various decay products of ^{238}U or ^{235}U, especially ^{230}Th, ^{231}Pa, and Pb isotopes. Material with ages of 10,000 to 350,000 years can be dated. The ratio of $^{235}U/^{238}U$, usually in shells, can yield dates in the 40,000- to 1,000,000-year range (Muhs and Szabo, 1982). The theoretical basis for young U dating is somewhat murky, but these techniques can span the gap between ^{14}C and K-Ar dates, especially in carbonate shells and similar materials. A major problem is the lack of suitable material to date.

Closed system decay of ^{238}U to ^{230}Th yields ages in the range of 10,000 to 300,000 years. The U-Th method has not been carefully calibrated and may give "young" apparent absolute ages due to removal of reactant. It generally yields consistent relative ages between deposits, especially if dated material is pedogenic carbonate drawn from the densest inner core of carbonate-coated gravels. The absolute age reliability of this method is not established.

Fission track dating is mainly limited to minerals (e.g., zircon, apatite) with fissionable U in volcanic rocks. Low annealing temperatures can cause unreliability, although this is not a serious problem in late Quaternary rocks. Some interpretation is required in counting tracks. This technique, a good one if suitable materials are available, has no inherent limitations on age range.

Thermo-luminescence (TL) dating depends on TL light intensity, which is related to crystal defects derived from spontaneous radioactive decay. A linear relation between induced radiation and TL intensity is assumed. Age calibration of TL glow curves may be difficult. Reheating may destroy TL defects. The maximum age is about 10^6 years. Ages may be 5% to 15% too "young" relative to K-Ar dates. TL dating is best for stratigraphic correlation and relative ages, rather than absolute ages.

Electro-spin resonance (ESR) has been used for dating fault gouge, but has only been tested once in Japan, using ESR in quartz. It requires formation of quartz in the gouge during the fault event (Ikeya and others, 1982).

Other Quantitative Numerical Techniques. Dating using paleomagnetism requires suitable material, with sufficient stratigraphic and time ranges to expose an adequate number of reversals, criteria not commonly found in fault trenches. An independent time datum is needed for unambiguous correlation with the polarity time scale. Paleomagnetic dating is time consuming and labor intensive.

The thickness of weathering rind developed on clast margins, such as that developed by obsidian hydration, can be used to estimate the age of deposits (Colman and Pierce, 1981). Climate and lithology must be consistent among deposits. It must be possible to calibrate rates of rind formation for a given lithology and climate. The method requires statistical analyses of a large data base.

Cation-ratio dating of desert varnish (Dorn, 1983) is limited to arid regions. The measurement of the ratio of K-Ca/Ti in varnish on rock surfaces requires precise chemical analysis. The method requires calibration by deposits or rocks of known age, but it holds promise.

Tephrochronology, the identification and correlation of undated and dated volcanic ashes, requires suitable ash deposits and detailed geochemical and petrographic analyses (Sheets and Grayson, 1979; Self and Sparks, 1981).

Dating using amino-acid racemization is based on the assumption of time-dependent diagenetic conversion of one form of amino-acid polymer structure to another (Bada and Helfman, 1975; Bada and Protsch, 1973). The method uses organic material and requires calibration of the rate of racemization. Environmental factors such as temperature and pH, as well as the type of material, may affect racemization. Good absolute ages are difficult to get.

Lichenometry estimates ages from the size of lichens on gravel or boulders (Locke and others, 1979). Lichenometry is limited to certain specialized environments, such as young glacial deposits. Corrections must be made for lichen types and the effects of clast composition, substrate position, and climate.

Soil-profile ages can be estimated from measured amounts of accumulated pedogenic materials (e.g., Machette, 1978). Rates and mechanisms of carbonate influx must be assumed; no carbonate must have been removed. Careful laboratory measurements of soil carbonate must be made. The best dates are obtained if soil ages are calibrated independently, but this method can yield potentially good estimates of soil ages. Other soil material can also be used, such as B-horizon clays and Fe-oxide accumulations in the B-horizon. Direct radiometric dating of soils is difficult and commonly misleading, as soils are generally open systems for ^{14}C and other radionuclides.

Dendrochronology can be used to determine ages of trees disrupted by faulting or fault-related phenomena such as landsliding (Page, 1970; Sieh, 1978b). Dendrochronology, useful for recent fault events (<8,000 years), is limited by the availability of suitable trees, by errors in the master chronology, and by requiring trees near the fault that are affected by processes related to rupture.

Relative Age Dating. Relative age dating, which involves relative age assignment to suites of deposits, is the least reliable and least precise method of dating. In some cases, crude age estimates may be inferred by correlation with dated deposits or with sequences with better age control. Relative age dating is generally based on the relative degree of soil-profile development or on the relative degree of weathering.

In many cases, the relative degree of soil profile development (chronosequence) in either buried soils or relict surface soils on surficial deposits (Machette, 1982) is the only available age indicator. In the B-horizon, the diagnostic soil-profile characteristics are thickness; depth; amount, texture, and type of clay; soil structure and color; and amount of Fe-oxides or Fe-Al-organic accumulations. In the C-horizon, the thickness, depth, stage of development, and amount of pedogenic carbonate and other soluble salts (gypsum, halite, etc.) are used. Techniques range from careful laboratory measurements (McFadden and Tinsley, 1982; Machette, 1982) to field description of soil profiles. Field descriptions are most useful when data are converted to a numerical index, such as that used by Harden (1982), that allows semi-quantitative comparisons. The estimated resolution and accuracy varies with degree of quantification of soil-profile characteristics and the age of the soil. The resolution decreases with increasing soil age. Resolution also depends on the degree of age calibration in the soil chronosequence. For Holocene and late Pleistocene soils, the resolution is $\pm 10^3$ to 10^4 years; for mid- to late Pleistocene soils, $\pm 10^4$ to 10^5 years; for older Pleistocene soils, 10^5 to 10^6 years. This is probably the most widely used technique for assigning relative or crude absolute ages to Quaternary deposits. The problems include factoring out soil properties related to parent material, climate, topography, and organic material from those related to time. Adequate age control for soil chronosequences is commonly difficult to achieve; however, at least order-of-magnitude estimates of the ages of Quaternary deposits can be inferred in most settings. Matti and others (1982), Pearthree and Calvo (1982), Pearthree and others (1983), Keller and others (1982), and Chadwick and others (1984) have given examples of such estimates in fault-offset studies.

Ages may also be estimated by evaluating the relative degree of weathering of surface and subsurface clasts in sedimentary deposits such as glacial moraines. Pertinent data include the percentage of a given lithology preserved; pitting of clast surface; clast splitting; and degree of weathering of a given lithology. A statistical, quantitative data base is obtained by taking measurements at a number of different outcrops. Climate and clast lithology often complicate the data base and may limit analysis. The method also requires some independent means of age calibration for a given suite of deposits. It is useful in conjunction with soil-development or weathering-rind data.

Assessment. The use of absolute age determinations is limited by their resolution and the age interval that may be dated. For young deposits, ^{14}C dating is the standard technique. For older deposits, various techniques, many of which contain serious limitations, are used; none serve as a standard. Relative age determinations are crude and are strongly dependent on environment. One of the major shortcomings of quantitative probabilistic studies on the effects of tectonics is the imprecision of age determinations.

Types of Quaternary Features Used for Recurrence Studies. This section discusses the types of Quaternary deposits, stratigraphic indicators, or fluvial features that have been used in fault-rupture studies.

Stratigraphic Sequences: Quaternary Sedimentary Deposits. Fault-related or -controlled deposits may occur within or adjacent to a fault zone, such as sag-pond fill (Sieh, 1978a, 1984), antithetic graben fill (Weldon and Sieh, 1985; Swan and others, 1980), and colluvial wedges derived from paleo-scarp degradation (Swan and others, 1980; Weldon and Sieh, 1985; McCalpin, 1982). Colluvial wedges present a special problem, as it is often difficult to relate them to specific rupture events.

Alluvial fans, debris cones, fluvial terrace deposits, and lacustrine shoreline deposits may be ruptured by or extend across a fault zone (Pearthree and Calvo, 1982; Matti and others, 1982; McCalpin, 1982). They may be deposited in response to nontectonic factors (i.e., climatic change) of potentially very different age from the time of rupture; thus rupture ages may only be estimated by bracketing between ages of faulted and unfaulted deposits (with potentially poorer resolution).

Other Stratigraphic Indicators: Landforms and Stratigraphic Features Inferred to Reflect Earthquake Motions Related to Fault Rupture. Stratigraphic indicators of earthquake shaking in unconsolidated sediments include sand boils, mud volcanoes, or other liquefaction-related features. In some cases, the presence of such features associated with a rupture event has been used to infer minimum earthquake magnitude (Sieh, 1978a; J. E. King, 1978; Youd and Perkins, 1978; Russ, 1982; Cox and Talwani, 1984; Obermeier and others, 1985).

Earthquake-induced landslides, slumps, rockfalls, disrupted lake sediments and soil horizons, and earth or soil flows are useful if one can establish a clear relationship to earthquake intensity and timing along a fault zone (Keefer, 1984; Youd and Perkins, 1978; Youd and Keefer, 1985; Adams, 1981). The earthquake must be dated.

Shear zones, cracks, and fissuring may also be related to earthquakes or tectonic strain (Zellmer and others, 1985). Some means of dating, or of relating these features to dated deposits, if a crack occurs in stratigraphic sequence, must be available.

Offset, Displaced, or Anomalous Landforms. Amounts and ages of fault ruptures can be estimated from offset or displaced landforms such as stream channels, fluvial terraces, and marine terraces. Stream-channel offsets are especially useful in unraveling lateral displacements on transcurrent fault zones, which cannot be directly observed in vertical trench walls (Keller and others, 1982; Sieh, 1978b; Sieh and Jahns, 1984). Abrupt thickening of alluvial channel deposits across a fault zone may record recent faulting as well (Bull and others, 1979). Stream-channel offsets can also be used to infer vertical uplift rates (Hamblin and others, 1981). It must be possible to correctly correlate active and potentially inactive paleochannels across the fault zone. Good preservation of older paleochannels and good age control (usually obtained by determining age of a deposit or surface underlying the paleochannel, or by dating units above paleochannel gravels) are also needed. The method works best in combination with stratigraphic offsets.

One or more offset fluvial terraces or alluvial fan surfaces along a stream that crosses a fault zone may record vertical or lateral displacements (Suggate, 1960; Lensen, 1964, 1968). Terraces that record multiple successive offsets along a fault are especially valuable; in this case, it is possible to develop a detailed time-progressive history of vertical, horizontal, and oblique displacements. Data requirements include the ability to correlate and recognize terraces across a fault zone; terraces that are traceable down- and upstream for some distance; and a well understood terrace form and longitudinal profile (particularly to determine vertical offsets) (Bull and others, 1979; Hamblin and others, 1981; Rockwell and others, 1984). If tectonic in origin, terrace formation occurs at the time of rupture; if of climatic or other origin, the terrace brackets age of faulting. Thus it is necessary to determine the origin of the terrace, most commonly by comparing the longitudinal profile of terrace to modern channels. Because of base-level fall and the resultant stream incision along the fault where the stream crosses it, the profiles of tectonic terraces diverge downstream toward the fault zone.

In addition, some means of dating the terraces is required. This is generally done by either dating the underlying terrace deposits or by estimating the age of the surfaces by the degree of soil development. In general, paired strath terraces are least ambiguous for this type of analysis. A well preserved flight of successively offset or warped, laterally traceable terraces, with good age control, can provide a fairly detailed history of a recurrent fault. The history may be treated statistically and converted to fault slip rates; however, these situations are rare.

Uplifted flights of marine terraces can be used to estimate the ages of a series of earthquake or fault events (Matsuda and others, 1978). Problems include correlation of individual terrace levels with an earthquake origin, i.e., determining that the uplift of terraces is co-seismic and not related to larger-scale coastal uplift or sea-level changes. Terraces must be dated adequately as well.

Assessment. Stratigraphic sequences are probably the best single data source for fault recurrence studies, especially when deposits are explored in trenches across the fault zone and when they contain good radiometric age control (e.g., Sieh, 1978a, 1984). A good stratigraphic sequence, with multiple deposits of varying ages, is especially useful, if not required, for resolution studies of active faults like the San Andreas fault zone. For other stratigraphic indicators, one must be able to exclude features of nontectonic origin, such as those formed in anomalous climatic or weather conditions. Offset, displaced, or anomalous landforms must be well preserved and bear a clear relationship to faulting events. The ages of these features are usually obtained by dating of underlying or associated deposits, by using soil development to obtain the age of a geomorphic surface, or by extrapolation from a few dated geomorphic surfaces in a sequence, assuming some constant slip rate (Weldon and Sieh, 1985). Some assumptions as to constancy of slip rates are required; thus slip rates must be independently checked. This method works best if it is combined with soil-profile data.

Stream-Profile Analysis. Stream-profile analysis estimates the presence, age, and possible amounts of fault movement by determining the size and position of anomalous inflection points (knickpoints) in the longitudinal profile of a stream above a fault zone.

Method. Stream-profile analysis requires detailed profiling of stream channels and terraces and isolation of any knickpoints (Reed, 1981). The analysis models rates of knickpoint retreat up the stream channel from the original point of offset where the stream crosses a fault. Modeling uses either an exponential decay law (Hamblin and others, 1981) or a diffusion equation (Begin, 1983; Begin and others, 1981; Mayer, 1979, 1982; Mayer and others, 1981).

Results. Stream-profile analysis usually provides approximate estimates of the amount of faulting and an approximate to precise estimate of the age of faulting.

Data. This method requires some important assumptions about the origin and type of modification of observed knickpoints. Knickpoints must result from a past fault-rupture event and not be related to a bedrock feature in the channel. Quantitative modeling of knickpoint ages assumes that knickpoints migrate upstream after their formation instead of remaining stationary while declining in slope (although knickpoints probably decline in slope as they migrate). Diffusion modeling requires the additional assumption that knickpoint retreat mimics a heat/mass-flux, a process mathematically described by the standard two-dimensional continuous diffusion equation for heat conduction. The rate-mass flux constant must be calibrated for each stream.

Limitations. Small-scale knickpoints resulting from single events are probably not long preserved on large streams (Hamblin and others, 1981), but may be preserved in gullies crossing fault scarps. Only large-scale, multiple, and compounded offsets are observable on larger streams. There are many difficulties in calibrating the rate constant for the diffusion equation (Begin, 1983). Recognizing knickpoints and establishing that they are tectonic in origin may be difficult.

Assessment. Diffusion analysis of knickpoints is a relatively new but promising analytical technique requiring additional testing. At present, results are only qualitatively useful.

Fault-Scarp Morphology. The age of fault displacements (usually the most recent, although in some cases, one or more prior events) can be estimated directly from the morphology of the topographic fault scarp produced by the associated surface rupture.

Method. Several techniques are currently available for morphologic age estimation of fault scarps. All use the same basic data source--field-based topographic profiles oriented perpendicular to the scarp trace. The key data are scarp height and maximum slope angle and identification of steeper versus more gently inclined slope segments if the scarp is composite (reactivated scarp with more than one rupture episode). Wallace (1977) produced initial deterministic age estimates, based on a graph of maximum slope angle vs. age. His results were poorly constrained by independently dated scarps and had poor age resolution (order of magnitude only).

Bucknam and Anderson (1979) introduced a more rigorous, quantitative (statistical) and better age-calibrated method. They noted systematic variation of maximum slope angle with height for a given fault scarp, definable by linear regression of maximum angle versus the log of scarp height. The regression line changes position and angle of slope with increasing age of fault scarps. Thus the age of an undated scarp can be estimated by comparing its height-angle regression with those of dated scarps (or in a specific case, with dated Lake Bonneville shorelines). Machette and McGimsey (1982) and Machette and Personius (1984) illustrated this approach. Mayer (1982, 1984) improved on the method by adding 95% confidence limits to the reference scarp-regression lines and by using discriminant function, statistical analyses to assign the height-slope data of undated scarps to one of several dated reference scarp data sets. Nash (1980) first applied the diffusion equation as a means for estimating rates of fault-scarp degradation. His early work used a graphical technique to assign age estimates to undated scarps, based on a finite-element solution to the original diffusion equation. Mayer (1982) computerized the technique; he emphasized the use of multiple profiles of a given scarp to allow more stochastic analysis of natural variations in topographic form. Hanks and others (1984) and Colman and Watson (1983) offered means to analytically solve the diffusion equation based on a given topographic profile. Nash (1984) also offered alternative graphical trigonometric means for solving the diffusion equation for a given profile.

Results. These methods offer the first really promising means of directly estimating the age of the topographic expression of a surface fault rupture. The height/slope-angle regression methods generally yield at least an order-of-magnitude age estimate and are generally reliable to about 10^3 years for scarps less than 10^4 years old. Resolution decreases on older scarps ($\pm10^4$ years). The diffusion-equation solutions provide more precise numerical ages, with estimated accuracies of $\pm$30% to 60% (Nash, 1984). Morphologic ages are best considered as broad age ranges.

Data. Dating using fault-scarp morphology requires several important assumptions and restrictions. The fault scarp is assumed to reflect the surface manifestation of faulting at depth. This assumption is supported by recent seismic-reflection profiling across fault scarps (Crone and Harding, 1984) and observations of recent earthquake traces (Crone and Machette, 1984) and associated shear zones. Care must be taken to determine that a scarp is of tectonic origin, however, and not related to other geomorphic processes such as stream erosion or land subsidence due to human intrusion.

Fault-scarp height is assumed to be a reasonable proxy for tectonic displacement; usually tectonic displacement represents about 50% to 70% of topographic height. Machette and Personius (1984), Wallace (1980), and McCalpin (1982) offered means of calculating displacements from scarp height.

More importantly, all morphological age estimates are based on the assumption of a consistent sequence of time-progressive scarp degradation (first outlined by Wallace, 1977)--essentially a slope-decline model, with a well defined time of initial rupture.

Morphological variations between fault scarps are considered primarily dependent on age differences; thus care must be taken that other factors, such as climate, slope aspect, scarp parent material, scarp gullying and so forth, are constant, especially between dated reference scarps and undated scarps. Fortunately, age estimates do not seem overly sensitive to small variations in these factors, given the broad resolution of the method.

Linear-regression analyses require at least 5 to 10 profiles of varying height along the same scarp for reliable age estimates; obtaining so many profiles is not always possible.

Diffusion-equation solutions require determination of the critical rate constant (k), which is assumed to incorporate the combined effects of the other non-time-related factors. This usually requires solution for k on a dated fault scarp of similar parent material, climate, and so on; finding a similar, dated scarp is sometimes difficult.

Uniform past rates of scarp degradation must be assumed, but late Pleistocene scarps and Holocene scarps in areas where climatic changes have significantly affected slope vegetation and erosion processes may not have similar rates. This affects diffusion more than the regression analyses, as the rate constant k may change with climatic regimes.

Morphologic age estimates are most suitable for single rupture scarps, where the entire scarp forms at once. There is some controversy as to applicability of these techniques to composite scarps, in which the effects of successive ruptures are superimposed on a previously degraded scarp. Sometimes the latest event can be isolated as a steeper short segment if recurrence times are long. With shorter repeat times, single events tend to merge together. Nash (1980, 1984) restricted analyses to single-event scarps; Mayer (1982, 1984) thought that the precision of the method depends on recurrence time and age of last rupture. Hanks and others (1984) applied diffusion-equation modeling to composite scarps as well as single-event scarps. All things considered, it is probably best to work with single-event scarps, using progressive offsets of older surfaces or deposits to infer prior ruptures and repeat times, and to restrict morphologic age estimates to clearly segmented composite profiles (Mayer, 1984; Machette and Personius, 1984).

Fault rupture is also assumed to occur along a single, spatially restricted zone, creating an initial free-face vertical step, and not distributed over a complex rupture zone, because a complex rupture alters the assumed initial scarp configuration (Mayer, 1982, 1984; Nash, 1984).

It must be possible to calibrate age estimates. This usually requires one or more fault scarps with independent age control and with similar climate, parent material, and so on.

Care must be taken in topographic profiling to record scarps with no complicating factors like gullying or man-made disturbance and with relatively well-preserved upper and lower surfaces. Ideally the upper and lower original surfaces are exposed above and below the scarp. On many higher scarps, however, the lower surface is buried beneath slope-wash material derived from scarp degradation or from adjacent alluvial fans. This yields a minimum estimate of scarp height, which usually affects offset estimates more than age estimates.

This method is mainly sensitive to scarps with at least some vertical separation. Other methods are required for primarily lateral-separation (transcurrent) faults.

The position of a scarp at or near the base of a larger escarpment or mountain front will influence the rates and processes of scarp degradation.

Limitations. The most significant limitations are lack of independent age control for scarps, the presence of large composite scarps without segmentation in the profile, complex rupture events, lack of height variation along scarp (for regression analysis), extensive scarp dissection, and variations in profile morphology and aspect perhaps due to climate, bedrock variations, and so forth.

Assessment. Despite the limitations of this technique, results to date from a number of studies suggest that morphologic age estimates are surprisingly robust and are applicable in some form (regression or diffusion) to most scarps, especially piedmont scarps. However, it is best to state results in broad age ranges, to incorporate more than one profile or scarp in analyses, and to calibrate results against age constraints provided by offset stratigraphy. The final result of these analyses is the estimated age of one or more ruptures, recurrence intervals, or slip rates. Statistical analyses and probabilistic reduction of future fault-rupture behavior are subject to the same interpretational problems discussed earlier with respect to offset stratigraphy.

Vertical Crustal Movements

The analysis of vertical crustal movements requires identification of recent long-term movements of the crust. This review emphasizes vertical displacements not necessarily focused along a specific structure or narrow structural zone, but instead distributed over a large region (up to epeirogenic scales). The discussion focuses on tectonic zones of uplift or subsidence, although other, nontectonic processes can induce large-scale movement (e.g., isostatic adjustments, salt or mud diapirs, ground-water dissolution or withdrawal).

Two major types of analytical methods that differ in scale and resolution are used to quantify vertical crustal movements. Geophysical methods, primarily geodetic leveling surveys, are directed primarily at small vertical displacements over short (historical, 10 to 100 years) time intervals (Reilinger and others, 1984; Riecker, 1979; Brown, 1978b; Brown and Oliver, 1976). The validity of leveling data for interpretation of tectonic strain is controversial. Geologic methods are sensitive to larger movements over longer time intervals (10^3 to 10^{6}+ years). The focus of this part of the discussion will be on geologic methods, which fall into several categories: analysis of fluvial adjustments, such as changes in longitudinal profiles and terraces, regional dissection patterns, and map-view channel patterns; evaluation of marine and lacustrine terraces, shorelines, or deposits; use of other geologic indicators such as lava flows; and quantitative models of geologic processes.

Fluvial Adjustments. Fluvial systems are sensitive to vertical changes within their drainage basins. The methods discussed below identify patterns of vertical or lateral fluvial adjustments and attempt to isolate those of tectonic origin from those arising from such perturbations as regional climatic change, complex responses of fluvial systems, normal stream evolution, and so forth.

Method. Longitudinal profiles or fluvial terrace profiles identify amounts and rates of uplift based on the forms of stream profiles and terraces (e.g., Huber, 1981). There are two methods: analysis of profile knickpoints and of fluvial terrace profiles. Analysis of profile knickpoints is an attempt to isolate knickpoints in stream profiles and qualitatively or quantitatively (using diffusion-equation modeling) evaluate knickpoint data in a fashion similar to knickpoint analysis for fault rupture. Knickpoints associated with vertical movements are commonly larger than those associated with faults; are found on larger, more regional river systems; and include composite effects of multiple offsets (if tied to one specific structural zone), with consequent decrease in potential resolution of uplift effects.

Fluvial terrace profiles can be used as indicators of paleo-stream channels to isolate older intervals of uplift. The age of a terrace is inferred from the relative degree of soil-profile development or from dated deposits. The anomalous pattern sought is downstream divergence of terrace longitudinal profiles relative to each other or to modern channels. Downstream profile divergence is indicative of downstream base-level fall at or following the time of terrace formation. Downstream divergence, followed by convergence, isolates the probable zone of relative uplift. Downstream profile convergence is less diagnostic, as nontectonic processes, especially climatic change in the catchment basin, can produce this pattern.

Results. Fluvial terrace profiles can indicate amounts, rates, and possible locations of uplift at either local or regional scales. The possible resolution varies, ranging from meters/100 yr to meters/10^6 yr.

Data. For stream-channel profiles, either topographic maps (generally satisfactory for large areas or large uplifts) or detailed field surveys can provide the required data. For terrace longitudinal profiles, the relative heights of the terrace above the modern channel must be measured, and terrace remnants downstream must be correlated. Extensive field studies are usually required, including a series of elevation transects up flights of terraces, possibly augmented by topographic maps. Mayer's (1982) longitudinal analysis of the Colorado River and its tributaries in the western Grand Canyon established cumulative uplift due to faulting along Grand Wash Cliffs. Begin and others (1981) developed an experimental and theoretical derivation of this type of analysis.

Limitations. Good topographic maps and well-preserved or at least correlative terrace remnants must be available for these studies. Terraces that are traceable for large sections of a river profile, with minimal large gaps requiring long-range correlations, are most reliable. Knickpoints and terrace-profile anomalies must be tectonic in origin and not controlled by bedrock variations or normal convergence of climatic fill-terraces. Either a diffusion constant for knickpoint analysis or good control on the ages of terraces must be available.

Assessment. The resolution of uplift location and rate is generally broad and relatively imprecise. Timing data are often poor. Nontectonic processes can strongly influence interpretation. These methods are not particularly useful for quantitative studies.

Regional Patterns of Dissection or Degradation. Regional dissection or degradation can be used to infer presence, amounts, and minimum rates of regional uplift based, first, on comparison of modern and paleochannel profiles (without specific knickpoints or terrace profile divergence) (Hamblin and others, 1981); and second, on uplift rates inferred from regional denudation rates (Ahnert, 1970).

Identification of regional dissection (long-term valley downcutting) is based on reconstruction of paleochannels by inverted topography, where a dated unit such as a lava flow or geomorphic surface overlies channel deposits adjacent to and above the modern channel (Hamblin and others, 1981).

Method. This technique includes plotting and comparing modern and paleolongitudinal profiles, calculation of minimum mean downcutting rates (from the age of the overlying dated deposit and the amount of subsequent downcutting), and direct conversion into maximum uplift rates.

Results. Mean uplift rates are obtained in meters/10^3 to 10^6 yr, with highly variable resolution (dependent on the time datum).

Data. For best results, an inverted topography or dissected landscape with some dateable upper horizon is necessary, preferably with more than one dated time-line or horizon. Without time control, one can estimate the presence of probable uplift, but cannot establish any limits on rates or timing. For minimum ambiguity, the longitudinal profile of an older inverted channel should be compared with the modern profile. Similarity in profile form (but not in elevation) suggests reestablishment of an equilibrium profile following or during uplift (Hamblin and others, 1981).

Limitations. Uplift estimates are mean rates, averaged over the entire interval of downcutting since the formation of an upper time datum (such as a lava flow). The estimates are maximums, because downcutting may have begun some time after the time-datum or have ended before modern channel development.

Assessment. Inverted or well-dissected topography and well-dated deposits must be present for this method to provide quantitative results. This combination of circumstances is rare in North America outside the western United States. The window for rate estimates is relatively broad.

Regional Denudation. Regional denudation can also be used to estimate ages. Ahnert (1970) correlated measurements of mean denudation rates with the amount of relief in large denudations. From relief data, he provided a means of estimating order-of-magnitude uplift rates, given certain assumptions.

Method. Mean relief of a large drainage basin is measured, using some systematic sampling scheme. Relief data are converted to an estimate of the uplift rate using an equation derived from regression of denudation-relief data from 20 control basins, assuming certain rates of summit denudation and relative rates of stream incisions (Ahnert, 1970).

Results. Uplift rates are estimated in meters/10^3 yr, with an order-of-magnitude error. Regional denudation is an indicator rather than a quantitative measure, because of the assumptions in the method. It is probably best applied to estimate general long-term uplift rates.

Data. Good topographic data and a systematic sampling scheme are needed. The method is relatively insensitive to minor variations in climate and requires no special geologic data such as dated lava flows or inverted topography.

Limitations. Basic assumptions built into method, such as the relation between summit lowering and mean denudation, strongly affect the estimated uplift rates. The sampling scheme used can strongly bias results.

Assessment. This method depends strongly on sampling strategy and assumptions about denudation rates. Large potential errors are possible; the method is qualitative rather than quantitative.

Anomalous Map-View Channel Patterns. In some cases, anomalous map-view channel patterns can be related to regional tectonic uplift or subsidence. Adams (1980) and Ouchi (1985) related observed changes in channel sinuosity to zones of uplift, subsidence, or tilting. Ouchi (1985) also conducted flume experiments to document channel changes under controlled base level changes. Nansen (1980) measured anomalous preferred directions of meander migration, which he attributed to regional tilting.

Method. Specific channel patterns, such as degree, amount, and directions of channel sinuosity (stream channel length/valley length), braided versus meandering profiles, abrupt changes in aggradation versus degradation, and so forth, are identified and measured.

Results. An anomalous channel pattern mainly indicates distribution, presence, and amount of uplift, tilting, and so on, during fairly recent times. The estimates are difficult to convert to tectonic rates unless some longer-term time control is available. Adams (1980) estimated a "numerical age" for tilting, assuming a sudden start and a uniform rate of deformation. Age bounds can also be established using the age range of floodplain deposits (dated deposits or degree of soil development).

Data. Identifying and quantifying sinuosity and other channel patterns requires good aerial photographs and topographic maps.

Limitations. The results of this technique, especially deformation rates, are difficult to quantify. The channel patterns must have a tectonic origin. The method is most reliable if strong anomalies exist on a given profile or if systematic changes occur on several river systems regionally. It is generally difficult to establish the age and duration of the tectonic deformation.

Assessment. These techniques provide some measure of potentially subtle, low-level tectonic processes over time spans between geodetic and most geologic data (10^2 to 10^3 years).

Marine and Lacustrine Terraces and Shorelines. Anomalously high or distorted elevations of dated marine or lacustrine shoreline landforms or deposits may indicate uplift or warping. Marine terraces have been studied by Chappell (1974), Bloom and others (1974), Chappell and Veeh (1978), Pillans (1983), and McLaughlin and others (1983). Lacustrine terraces were discussed by Williams (1982) and Lucchitta (1979).

Method. Altitudes of marine or lacustrine features are identified and measured, and ages of features are established as precisely as possible. For marine terraces, mean sea-level fluctuations are removed using sea-level curves derived from either tectonically stable control areas (e.g., Bahamas) or areas with probable uniform uplift rates (e.g., Barbados, parts of New Guinea). Rates of uplift are inferred from anomalous elevations versus age of feature.

Results. Studies with abundant time control can yield fairly accurate estimates of uplift rates, in meters/10^3 to 10^4 yr or even mm/yr.

Data. Typically, field surveys normal to coast shorelines or terrace flights, sometimes augmented with topographic maps, are needed to establish elevations. Terraces are usually dated by U-series or U-Th of shells on terrace levels (the best control), amino-acid racemization, or ^{14}C. In some studies, dating has been restricted to several control points, and ages have been extrapolated to the rest. Some studies have fitted best-fit regression lines to height-age data to estimate uplift rates.

Limitations. The use of these methods is restricted to areas with coastal terraces or good lacustrine features. Independent age and water elevation controls are needed. It must be possible to reliably factor out effects of sea-level changes in Pleistocene time (usually by extrapolating observed height from elevation predicted by sea level alone, without tectonic uplift). Problems in establishing a morphologic datum on a terrace to measure height are of particular concern where the terrace is mantled by postuplift alluvial fans or eolian sediments, or where the terrace is highly dissected.

Assessment. Age control is critical; without dateable materials, this method gives only approximate information. In suitable areas, particularly along active coast lines, it can yield acceptable regional uplift rates. The method is generally less quantitative for fluvial systems than for marine systems.

Correlation of Tectonics and Seismicity

A seismic hazard analysis, which calculates the probability that some level of earthquake ground motion will be exceeded at a repository site, depends on three critical sources of data. These are identification of the earthquake source (faults or other tectonic features), an estimate of the magnitude of the earthquake that might occur within a given source, and an estimate of the ground motion that might result from the earthquake at the site (Housner, 1969; EPRI, 1985).

Preceeding sections of this chapter discuss some methods by which potential earthquake sources may be geologically identified and recurrence interval quantified. The section on basement reactivation in the discussion on non-predictive phenomena, below, describes additional physical characteristics associated with potential sources. Predictable ground motion at a repository site is the subject of Chapter 5.

The relationship between the earthquake source, its recurrence rate, and earthquake magnitude (and thus a prediction of the potential maximum earthquake magnitude) is the primary subject of this section. Studies of earthquake precursors and associated deformation play an essential role in understanding and predicting the magnitude of a future event. Therefore, a brief review of some important references in the tectonic and seismic literature on earthquake prediction leads this discussion.

Earthquake Prediction. Rather than exhaustively reviewing the literature in earthquake prediction (cf. Rikitake, 1976, 1982; Brown, 1978a; Ward, 1978; Simpson and Richards, 1981), this section notes some critical references. Prediction is based on the presence and interpretation of long- and short-term precursors, from which models and the assignment of probabilities are derived. As yet, efforts to predict times and places of earthquake occurrence have met with little success.

Long-Term Precursors. A critical data base for earthquake prediction is the historical record of earthquakes at local, regional, and plate scales (Ambraseys, 1971; Coffman and von Hake, 1973; Rikitake, 1982; Shimazaki and

Nakata, 1980; Veneziano and others, 1983). Recognizing the shortcomings of historical data (Allen, 1975; Veneziano and Coppersmith, 1985), various workers have attempted either to relate the historical data to phenomenological or statistical relationships such as Weibull distributions (Hagiwara, 1974), seismic gaps (Mogi, 1968; Sykes, 1971; McCann and others, 1978) and migration of seismicity (Gelfand and others, 1972), or to ascertain and rectify historical incompleteness (Stepp, 1972; Veneziano and Coppersmith, 1985).

Measurements of crustal strain comprise a second important source of data for identifying long-term precursors. This type of analysis describes the accumulation rate of strain (Langbein and others, 1983; Rikitake, 1974) and ultimate crustal strain (Rikitake, 1975b), as well as site-specific strain and geodetic measurements (Castle and others, 1976; Jackson and others, 1980; Prescott and others, 1979; Mark and others, 1981).

Short-Term Precursors. In active seismic areas, careful analysis of anomalous uplift (Rikitake, 1976); changes in sea level (Ota, 1975; Plafker and Rubin, 1978; Sato, 1977; Rikitake, 1975a; Wyss, 1975, 1976a, 1976b, 1977); crustal tilt, strain, or stress (Rikitake, 1984; Sauber and others, 1983; Jamison and Cook, 1980; McGarr and Gay, 1978; McGarr and others, 1982; Abou-Sayed and others, 1978; Keys and others, 1979); and even rainfall (Huang and others, 1979) can often yield interesting if not always significant information that may serve as a basis for earthquake prediction.

Seismologic precursors are extensively used (Ohtake and others, 1978; Acharya, 1984; Ebel, 1984; Kagan and Knopoff, 1976; Simpson and Richards, 1981; Kanamori, 1981; Von Seggern, 1982; EPRI, 1985). They include foreshock (Rikitake, 1982); anomalous seismic activity (Evison, 1977a, 1977b; Ishida and Kanamori, 1977; Sekiya, 1977); seismic gaps of the second kind (Ohtake, 1976; Ohtake and others, 1977); growth and decay of seismic activity (Rikitake, 1976); b-values (Hasegawa and others, 1975; Kier, 1984); source mechanisms (Gupta, 1975; Ishida and Kanamori, 1978; Lindh and others, 1978); hypocentral migration of microearthquakes (Engdahl and Kisslinger, 1977; Gupta, 1975); and changes in seismic wave velocity (Aggarwal and others, 1973; Rikitake, 1979b; Semyenov, 1969; Wyss, 1981).

In addition, other geophysical data offer potential for prediction. These include earth-tide measurements (Latynina and Rizaeva, 1976; Mikumo and others, 1977); geomagnetic, geoelectric, and other potential-field values (Raleigh and others, 1977; Barsukov, 1972; Honkura, 1978; Rikitake, 1979a; Smith and Johnston, 1976; Rikitake, 1982; Corwin and Morrison, 1977; Noritomi, 1978; Varotsos and Alexopoulos, 1984; Daowska, 1977; Morrison and others, 1979; Yamazaki, 1975, 1977; Hagiwara, 1977; Jachens and others, 1983); and ground-water data (Kovach and others, 1975; Merifield and Lamar, 1981; Moyle, 1980; Sato, 1977; Shimamura, 1982; Tagutschi and others, 1983; Wesson, 1981).

Quantification and Models. Various workers have attempted to quantify precursor information (Aki, 1981; Coats and Murray, 1984; Fedotov, 1982; Kagan and Knopoff, 1977; Rhoades and Evison, 1979; Vere-Jones, 1978) or to develop predictive models (Ward, 1978; Rikitake, 1982; Mallio and Peck, 1981; Anagnos and Kiremidjian, 1984; Bufe and others, 1977; Niazi and Mortgat, 1984). The results of such models are often the subject of debate (Kerr, 1979), although consensus about their practicality is sometimes reached (Reddy, 1983; EPRI, 1985).

Assessment. Long- and short-term precursors of moderate to large seismic events have been extensively studied and quantified. Quantification is generally based on probabilistic models and standard statistical analyses. One critical view of earthquake prediction is that great earthquakes are not random occurrences, that the historic record generally provides an inadequate data base for proper statistical and probabilistic analysis, and thus that deterministic models may be more useful. A second view suggests that earthquake risk cannot be expressed in deterministic terms because of the enormous uncertainties about the nature and location of future earthquakes. The most significant problem with earthquake prediction is probably the lack of acceptable models that explain why precursors work.

The usefulness of long-term precursors largely depends on historical records. The more complete the record and the larger the experience with a tectonic feature, the greater is the confidence in predictions. As a long-term earthquake predictor, the monitoring of crustal strain probably has more potential than historical records, especially in North American where earthquake records date back only a few hundred years. Crustal strain studies require repeated geodetic surveys and experiments to calculate the strain required for crustal failure that results in large earthquakes.

Short-term precursors are usually carefully monitored only in seismically active areas. One of the most reliable short-term precursors to large earthquakes is land uplift, although not all uplifts are followed by earthquakes. Changes in sea level, tilt, strain, and crustal deviatoric stress have all had mixed success in prediction studies, and each may be difficult to precisely quantify. Seismologic precursors are widely used for prediction and will continue to be important as the meanings of characteristic seismic and microseismic patterns are clarified. Premonitory earth tides are not widely accepted as precursors. Geomagnetic and geoelectric precursors are being intensely studied, and although some of the methods are subject to experimental error and their results are often highly interpreted, the potential exists for significant forecasting using these geophysical tools. No integrated theory that explains why changes in the potential fields occurs prior to large earthquakes has been developed. Geochemical precursors, such as anomalous radon concentration in ground water (C. Y. King, 1978; Aric and others, 1984; Huksson, 1981), have been very useful in earthquake prediction. Macroscopic phenomena, such as animal behavior, lights, and noises (Rikitake, 1982), are excellent very-short-term precursors, but are not considered temporally relevant here.

If a repository site is built in a seismically active area, potentially predictive data of the types discussed above can probably be obtained. However, if the problem of predicting future seismicity is dependent on the relationship between older, aseismic tectonic features and their potential as a seismic source, then analysis may be more difficult. This future seismicity can take the form of previously unrecognized earthquake potential (e.g., a large earthquake on a fault with very long--non-historic--recurrence interval); the reactivation of unrecognized or inactive crustal structures by new, amplified, or changing stress environments; or the development of new plate-stress domains associated with intraplate crustal and upper mantle motions (ductile shear zones, domes, rifts, hot spots, and so forth; cf. Campbell, 1978; Zoback, 1983; Sibson, 1984).

In summary, interpreting earthquake precursors reliably requires models of the fundamental tectonic processes that create the earthquake source. Adequate and acceptable models are not yet available. Furthermore, scientific understanding of intraplate tectonic processes and available data (for example, in North America those areas east of the Rocky Mountains and Rio Grande rift) are currently not adequate to assess causative models or describe sources of potentially large earthquakes with a high degree of certainty (EPRI, 1985). Similar problems are evident even in the more tectonically active western part of North America, exclusive of the intensely studied Late Quaternary-Holocene San Andreas fault system.

Fault Rupture and Seismicity. Fault models that relate rupture geometry to earthquake magnitude are based on empirical and theoretical relations between the area of fault rupture, average fault slip, and earthquake magnitude. With this type of model, it is theoretically possible to predict large-scale deformation patterns (Brown, 1978a).

Method. The relationship between fault geometry and earthquake magnitude has been extensively studied (Tocher, 1958; Aki, 1966; Brune, 1968; Kanamori and Anderson, 1975; Cluff and others, 1980; Swan and others, 1980; Wallace, 1981; Schwartz and Coppersmith, 1984; Shaw and Gartner, 1984). Generally these studies are of two types. One type relates rupture length to magnitude (Mark, 1977; Tocher, 1958; Bonilla and Buchanan, 1970). A second type considers seismic moment, the relationship between rupture area and displacement on the rupture surface (Aki, 1966; Brune, 1968; Kanamori and Anderson, 1975; Hanks and Kanamori, 1979). Seismic moment may also be related to stress drop (Geller, 1976; Purcarn and Berkhemer, 1982).

Results. In seismic-moment studies, the approximately linear relation between magnitude and rupture area (Kanamori and Anderson, 1975) allows one to predict the extent of rupture along a fault, and by inverting the data, to calculate an earthquake body-wave magnitude (Nuttli, 1983a; Veneziano and Coppersmith, 1985). Without inversion, the application of elastic dislocation models (Savage, 1972; Bischke, 1974; Savage and Hastie, 1966; Turcotte and Schubert, 1982) to a specific crustal volume can theoretically predict deformation patterns and the effective radius of deformation (Rikitake, 1976).

Data. The length, shape, depth, orientation, area, and amount of slip on the earthquake rupture surface, as well as the recurrence interval and history of the source feature, are critical parameters in this type of analysis. Length, shape, and surface orientation are measured topographically and bathymetrically. Depth and subsurface orientation are determined by geophysical means, generally by earthquake and reflection seismology. Area of slip is commonly measured after rupture and is based on length of surface offset, the seismologically active zone during rupture, and geophysically determined depth. This process is much more difficult, if not impossible, in aseismic areas. To obtain potential rupture area in aseismic zones, the geometry of the inactive rupture is often used to segment the fault zone into discrete lengths along which it is assumed to displace coherently. Alternatively, a percentage factor may be used to estimate rupture length (cf. Slemmons, 1982). The amount of slip is determined by surface offset on exposures of rupture surface, from focal mechanism data, and from seismic slip calculations. Recurrence interval is calculated from the historical earthquake record (cf. Nuttli, 1974, 1983b), with prehistoric geologic data sometimes added in active fault zones (cf. Sieh, 1984; Sieh and Jahns, 1984).

Limitations. The exposure of surface-rupture geometry may be limited by sediment, water, or erosion. Seismic activity may not completely delineate the areal extent of rupture in active zones; in inactive areas, the resolution of geophysical methods for exploring the crust may be severely limited. The historical earthquake record is generally not sufficient to constrain the maximum earthquake in a region (McGuire, 1977; Chinnery, 1979). The best constrained seismic-moment data come from interplate boundaries; continental interiors are largely unstudied, and empirical moment relationships may not be appropriate to intraplate tectonic settings (Nuttli, 1983b), although a scaling factor may be derived in some areas (Nuttli, 1983a).

Assessment. The prediction of the maximum magnitude of an earthquake (and thus the future deformation of a repository site) from the relationship between geologic features and seismicity associated with an earthquake source is a corollary problem to the prediction of earthquakes, with the same inherent difficulties. In seismic areas, satisfactory resolution depends on a combination of detailed seismologic information, experience with previous earthquakes in similar settings, and reliable geologic mapping of potentially active faults (Allen, 1975). For aseismic settings, these methods largely depend on the geologic characteristics of the region, along with intuitive perceptions and low-resolution geophysical data about the composition and fabric of the crustal lithosphere beneath the specific site and regionally, as well as comparisons with "like" features that are active elsewhere. In both seismic and aseismic areas, prediction of the magnitude of future events is largely based on the qualitative perception of the possible extent of rupture; few quantitative data exist (cf. Veneziano and Coppersmith, 1985), although the state of stress of a specific region provides quantitative limits on effective stress release (Zoback, 1983).

Critical Comparison of Various Methods

In aseismic areas, geologic methods best ascertain the potential of a tectonic hazard. Of these methods, the best possible data set is obtained when fault recurrence can be established using well-dated stratigraphic sequences to infer the number and ages of fault offsets. Because age is a critical parameter in recurrence studies, appropriate materials must be available for age dating to ensure reasonable precision. Relative age determinations are crude. In every case, the best data are obtained when there has been late Quaternary or Holocene tectonism and related sedimentation. Older Quaternary activity is imprecisely documented, and late Tertiary tectonism is understood only within a precision of $\pm 10^6$ years. Analysis of stream profiles and fault-scarp morphology offers significant potential for quantifying Quaternary tectonism, but the methods are not currently completely tested or acceptable. Regional studies on vertical crustal movements and their relation to tectonism are too broad and are usually imprecise geographically or numerically.

In seismic areas, fault recurrence can be quantitatively established using a combination of historical earthquake records, detailed seismic information along the tectonic feature, geologic mapping, and experience with similar seismic features elsewhere. The prediction of the maximum magnitude of an earthquake is possible along interplate boundaries. Inside continental plates, the lack of models describing processes that potentially could act on the plates severely limits the certainty with which deformation can be predicted.

At present, no tectonic or seismologic method is completely adequate to quantitatively assess, with a high degree of certainty, the probability of tectonic activity at a repository site.

Availability of Data Bases and Variables of Each

A number of high-quality data bases are readily available for the evaluation of tectonic and seismic phenomena; a few of the more significant are listed here by issuing organization. No attempt has been made to review these data except to note their nature.

Tectonic Data

The major sources of tectonic data are found in the publications of the US Geological Survey (USGS), state surveys of the United States, the Geological Society of America (GSA), American Association of Petroleum Geologists (AAPG), and the National Aeronautics and Space Administration (NASA). Most of these data are in the form of geologic and tectonic maps, photoimages, cross-sections, isopach and structural contour maps, and fence diagrams at various scales and by various authors. All are subject to technical review before publication, including the photoimages from NASA. Data quality is variable, but generally good to excellent.

For example, the USGS publishes a series of field maps (e.g., Ziony and others, 1974; Hadley and Devine, 1974; Howard and others, 1978; Machette and Personius, 1984), open-file reports (e.g., Bucknam and others, 1980; Gable and Hatton, 1980; Clark and others, 1984; open-file reports like these normally contain extensive references), and professional papers (e.g., Poppe, 1979; Wentworth and Mergner-Keefer, 1983). Similar publications are published by almost every state geological survey in the United States. The GSA and the AAPG also publish many maps, as well as their respective bulletins and reports (e.g., Sexton and others, 1982). NASA provides space photography and interpretation (e.g., NASA, 1979). The National Earthquake Hazards Reduction Program has generated major new sources of interpreted data for tectonic and seismic analysis (e.g., US Geological Survey, 1980).

Seismic Data

The major sources of data for seismic analysis come from the World Wide Standardized Seismograph Network (e.g., Oliver and Murphy, 1971), National Geophysical Data Center (NOAA, no date), National Oceanic and Atmospheric Administration (e.g., Coffman and von Hake, 1973), US Coast and Geodetic Survey (e.g., Stepp and others, 1965; Barazangi and Dorman, 1969), UNESCO (e.g., Rothe, 1972), and the National Academy of Sciences (e.g., DeBra, 1979; Brown, 1978a). Some of these data are raw seismic records on computer tapes; other data have been plotted and interpreted. Not all data are technically reviewed or formally published. Raw data are generally of high quality.

In addition, data bases are found in the journals of the major geophysical publishers, including the Bulletin of the Seismological Society of America (e.g., Doser and Smith, 1982; Stevens, 1980; Ryall and others, 1966), the American Geophysical Union (e.g., Zoback and Zoback, 1980; Wallace, 1981; Coppersmith and Schwartz, 1984), Elsevier (e.g., Lisitzin, 1974; Holdahl and Morrison, 1974; Smith, 1977; Brown, 1978b; Reilinger and others, 1984), and Birkhauser (e.g., Swanberg and Morgan, 1978). This material is all subject to technical review and is of good to excellent quality.

Huge amounts of unpublished data exist in reports and manuscripts submitted to the Nuclear Regulatory Commission (e.g., Chiburis, 1981; Shannon & Wilson, 1976) and DOE consultants (e.g., Fugro, Inc., 1980), and national laboratories (e.g., Powers and others, 1978; Aldrich and Laughlin, 1982). Much of this material is subject to at least in-house technical review.

Phenomena Not Presently Predictable by Previously Discussed Methods

Perhaps the most significant uncertainty in tectonic analysis of waste repository sites is the determination of hazard in areas where little or no seismicity exists and where Quaternary--late Tertiary sedimentation and/or evidence for tectonism are minimal or non-existent. The eastern United States is an important example of this type of environment. There the main strategy for hazard analysis is quantifying the regional state of stress; understanding the processes which cause this stress regime; and identifying and characterizing the tectonic features that may become hazards; that is, sources for significant earthquakes, preferential ground-water movement, and so forth (Coppersmith and Kulkarni, 1985). To a large extent, this approach entails the evaluation of inactive basement features with the potential to be reactivated.

Regional State of Stress and Strain

The first step in the tectonic analysis of aseismic or weakly seismic areas is the determination of the regional stress-strain regime. This is mainly done using in-situ stress determinations (e.g., Carr, 1974; Abou-Sayed and others, 1978; McGarr and Gay, 1978; Keys and others, 1979; Zoback and Zoback, 1980) within the context of the world-wide plate environment (Richardson and others, 1979). Any earthquake data from the region must be integrated into this data set, because there is often a spatial relationship between zones of weakness (and thus local stress-strain regimes) and earthquakes (Bollinger, 1973; Barstow and others, 1981), although this is not always the case (Smith and Bruhn, 1984). The strength of crustal materials can sometimes be predicted by this analysis, combining laboratory (Kirby, 1980) and seismic data (McGarr, 1984).

Geodetically (e.g., Mark and others, 1981; Reilinger and others, 1984) and geologically (e.g., Schwartz and Coppersmith, 1984; Bull, 1978a, 1978b) observed strain is also critical; the previous sections of this chapter discuss the geomorphic and stratigraphic indicators for such strain in detail.

Although in-situ stress can be measured with precision, the determination of strain is mainly dependent on interpreted geological observations (e.g., Prescott and others, 1979). Theoretical strain analysis can yield a broader regional picture (Reches, 1983). In any case, the final product requires time-consuming, site-specific data gathering and analysis.

Tectonic Processes

A second, more theoretical step in this analysis is the evaluation of the tectonic processes that may be acting on the region to yield the observed regional stress-strain patterns. A number of important regional tectonic processes have been suggested. The first is the stress regime created by the plate-tectonic process. Most modern authors consider trench-pull and associated traction on the subducted slab to be the critical force that generates stress in the plates (Chapple and Tullis, 1977; Richardson and others, 1979; Turcotte and Schubert, 1982; Turcotte, in Coppersmith and Kulkarni, 1985, p. 3--12). Additional significant stresses are created by thermal perturbations (e.g., Liu, 1980), ridge-push, variations in crustal and lithospheric thickness, membrane stresses from variations in earth curvature, and erosion and sedimentation (Turcotte, op. cit.).

In addition to plate stresses, the regional picture is complicated by more local phenomena such as stress corrosion and chemical effects within the lithosphere (Anderson and Grew, 1977; Etheridge and others, 1984); localized movement along zones of different mechanical properties (e.g., Negmatullayev and others, 1984; Sibson, 1984; McGarr, 1984); large- and small-scale lithospheric compositional (e.g., Campbell, 1978; Kane, 1977) or rheological (e.g., Byerlee, 1968; Kirby, 1980; Sibson, 1977) inhomogeneities; stress amplification (e.g., Segall and Pollard, 1980); enhanced fluid pore pressure (e.g., Bulau and others, 1984; Etheridge and others, 1984) and associated hydrolytic weakening of minerals such as quartz in the upper lithosphere (Sibson, 1981; Blacic and Christie, 1984; Kronenberg and Tullis, 1984); stress-induced crack growth in stressed regions (Crampin and others, 1984; Swanson, 1984; Segall, 1984); and brittle reactivation of previously ductile zones due to later uplift (e.g., Sibson, 1977; Watts and Williams, 1979; Cranwell and Donath, 1980; Passchier, 1982; Grocott, 1977).

The influence of each of the above processes has not been thoroughly tested in any regional context. Intuition demands that each may be important locally, but only the study of a specific region will ultimately resolve the relative importance of each factor. Undoubtedly additional relevant processes will appear in the course of analysis.

Tectonic Features

Finally, a map of the major tectonic features of the region must be created. This map depends on two critical sources of data: surface and near-surface geology, which can be obtained with some confidence; and sub-surface crustal and lithospheric features, which depend on generally low-resolution geophysical mapping and significant interpretation for their identification. Some of the more important tectonic features on which exploration should be focused are ductile shear zones in all regions of the lithosphere, particularly the upper and middle parts (e.g., Sibson, 1983, 1984; Sykes, 1978; Ratcliffe, 1983; Passchier, 1982); plutons (e.g., Campbell, 1978; Sykes, 1978); water at depth (e.g., O'Neill and Hanks, 1980) and other lithospheric inhomogeneities (e.g., Kane, 1977); and brittle fracture zones (Sykes, 1978; Sibson, 1983; Wentworth and Mergner-Keefer, 1983; Zoback, 1983).

Assessment

Predicting basement reactivation along pre-existing zones of weakness requires that these zones be recognized (generally by geophysical mapping); that the stresses and strains be measured around the structure; that the critical strain accumulation and mechanisms for failure be modeled and predicted; and that the tectonic processes that may cause seismic activity along the structure be delineated and quantified.

The critical assumption for earthquake hazard analysis in this situation is that once the stress regime acting on a known tectonic feature with predictable failure mechanism is understood, one may predict the magnitude and location of the seismic hazard. This assumption has yet to be tested, and not all the data necessary for such a test have been accumulated for any specific site.

A side benefit of the identification and characterization of tectonic features in this analysis may be information about other potential geologic hazards at the site, such as differential uplift or subsidence, ground-water invasion, thermal and geochemical anomalies, and so forth.

Evaluation of Best Method for Performance Assessment

A number of studies have attempted to outline procedures for performance assessment in tectonics and seismology (e.g., Geotechnical Engineers, 1980; D'Alessandro and others, 1980; Reddy, 1983). The major problems associated with such assessments are inadequate data collection; disagreement between professionals about the quality and significance of the data; significant uncertainty in the level of current scientific understanding and in the available data; and the inability to assign meaningful and generally accepted probabilities. A recent report by Dames & Moore (EPRI, 1985) is probably the best effort now available to develop methods for evaluating seismic hazard.

In order to understand the tectonic/seismic hazards of a region, three data bases were established in the EPRI study: the causes of crustal stress in the region; the present state of the regional stress regime; and the identity and characteristics of the tectonic features in the region that might produce moderate to large earthquakes. Thus, the critical information base for this method is a matrix of the physical characteristics of a region. This matrix includes tectonic mechanisms, magnitude and orientation of crustal stresses, crustal and lithospheric features, surface and sub-surface geology, and earthquake history. Data are collected from the literature and interpreted independently by six earth science teams.

The tectonic framework of the region is created by the following steps:

1. Identification of tectonic features, filtering the geologic data using criteria established in advance by a consensus of the earth science teams. These criteria include the size of the feature, type of fault motion expected, potential for large seismic event, and deep crustal expression.

2. Definition of the physical characteristics of each feature.

3. Definition of the earthquake potential of each feature, based on the known stress environment, orientation of the feature, and the tectonic processes that may act on it.

4. Assignment of a probability that a seismic event of some magnitude will occur.

Each earth science team independently constructed a tectonic framework; each framework was equally weighted relative to the others. Each team also ranked its own expertise on the region, allowing an independent ranking of the teams. The independent hazard estimates were then combined using a mechanical aggregation procedure, in which a weighted average of the individual results was computed; open exchange of information and data interpretations, as well as revisions of initial hazard assessments, were allowed throughout the process.

The major improvement made by this method is the establishment of a critical relationship between process and physical feature: a seismic event is the result of stress related to an on-going process acting on a specific tectonic feature. In addition, the aggregation procedure allowed quantitative statistical results to be developed for the assessments.

Major shortcomings of any method are a poor understanding of relevant tectonic processes, a lack of available data for a region or specific location, and the inability to test probability relationships in the real world.

Discussion of Currently Available Approaches

Data

As noted previously, the best current data for probabilistic prediction of the hazards of tectonic features are recurrence data based on stratigraphic sequences in areas where there has been late Quaternary or Holocene tectonism and related sedimentation. Collection of this type of data for a specific area is critical. In addition, a number of other data needs are clearly indicated: increased understanding of tectonic processes and their relation to the generation of a seismic event, based on laboratory and field data; refined and additional age-dating techniques for the Quaternary Period; a more complete and well understood historical record for seismic and tectonic events to allow testing of hazard methods by retrodiction; development of quantitative and repeatable methods for landform analysis; use of new geophysical techniques that provide either higher resolution (i.e., computer-enhanced seismic reflection) or new insight (i.e., seismic tomography) into crustal structure; increased understanding of material properties and rheology, including a realistic connection between field and laboratory studies in the geologic time domain; and statistical methods for evaluating the divergent probability estimates of earth science experts.

Implementation of Methods

As previously discussed, I feel that a method such as that outlined in the EPRI report offers great potential. To implement this approach for a specific area, the following steps would be required: form a set of teams of earth science experts, each team containing a broad range of expertise; formalize the method for evaluating and ranking hazard assessments made by these teams; develop a consistent and generally accepted method for assigning probabilities to hazards; and, most importantly, testing of such analyses by retrodiction: that is, applying the technique to a set of data in the Holocene or Quaternary in which historical data exist as well to see whether the analysis provides reasonable probabilities for events that have already occurred.

Conclusions

At present, no tectonic or seismologic method is completely adequate to quantitatively assess, with a high degree of certainty, the probability of tectonic activity that will create a hazard at a repository site. New methods and increased near-term scientific understanding may add significantly to the potential for making predictions; however, this will depend on significantly higher levels of interest in and funding for the problems of geologic prediction.

References

Abou-Sayed, A. S., C. E. Breshtel, and R. J. Clifton, 1978, "In-Situ Stress Determination by Hydraulic Fracturing: A Fracture Mechanics Approach," Jour. Geophys. Research, vol. 83, p. 2851-2862.

Acharya, H. K., 1984, "Changes in Volcanic and Seismic Activity Prior to Great Earthquakes," Earthquake Notes, vol. 55, 11 pp.

Adams, John, 1980, "Active Tilting of the United States Midcontinent; Geodetic and Geomorphic Evidence," Geology, vol. 8, p. 442-446.

Adams, John, 1981, "Earthquake-Dammed Lakes in New Zealand," Geology, vol. 9, p. 215-219.

Aggarwal, Yash P., Lynn R. Sykes, John Armbruster, and Marc L. Sbar, 1973, "Premonitory Changes in Seismic Velocities and Prediction of Earthquakes," Nature, vol. 241, p. 101-104.

Ahnert, F., 1970, "Functional Relationships Between Denudation, Relief, and Uplift in Large Mid-Latitude Drainage Basins," Amer. Jour. Sci., vol. 268, p. 243-263.

Aki, K., 1966, "Generation and Propagation of G-waves from the Niigata Earthquake of June 19, 1964," Bull. Earthquake Research Inst., Tokyo University, vol. 44, p. 23-88.

Aki, K., 1981, "A Probabilistic Synthesis of Precursory Phenomena," in D. W. Simpson and P. G. Richards, eds., Earthquake Prediction, An International Review, M. Ewing Series, vol. 4, Amer. Geophys. Union, Washington, DC, 680 pp.

Aldrich, M. J., Jr., and A. W. Laughlin, 1982, Orientation of Least-Principal Horizontal Stress: Arizona, New Mexico, and the Trans-Pecos Area of West Texas, LA-9158-MAP, Los Alamos National Laboratory, Los Alamos, NM.

Allen, Clarence R., 1975, "Geological Criteria for Evaluating Seismicity," Geol. Soc. Amer. Bull., vol. 86, p. 1041-1057.

Ambraseys, N. N., 1971, "Value of Historical Records of Earthquakes," Nature, vol. 232, p. 375-379.

Anagnos, T., and A. S. Kiremidjian, 1984, "Stochastic Time-Predictable Model for Earthquake Occurrences," Bull. Seismol. Soc. Amer., vol. 74, p. 2593-2611.

Anderson, O. L., and P. C. Grew, 1977, "Stress Corrosion Theory of Crack Propagation with Applications to Geophysics," Rev. Geophys. Space Phys., vol. 15, p. 77-104.

Aric, K., and others, 1984, "Radon Measurements for Earthquake Prediction Research," Progress Report, 1983, Vienna Univ., Austria, 23 pp.

Bada, J. L., and P. M. Helfman, 1975, "Amino Acid Racemization Dating of Fossil Bones," World Archeology.

Bada, J. L., and R. Protsch, 1973, "Racemization Reaction of Aspartic Acid and Its Use in Dating Fossil Bones," Proc. Nat. Acad. Sci. USA, vol. 70, p. 1331-1334.

Barazangi, M., and J. Dorman, 1969, "World Seismicity Maps Compiled from ESSA," Coast and Geodetic Survey Epicenter Data, 1961-1967, Bull. Seismol. Soc. Amer., vol. 59, p. 369-380.

Barstow, N. L., K. G. Brill, O. W. Nuttli, and P. W. Pomeroy, 1981, An Approach to Seismic Zonation for Siting Nuclear Electric Power Generating Facilities in the Eastern U.S., NUREG/CR-1577, US Nuclear Regulatory Commission, Washington, DC.

Barsukov, O. M., 1972, "Variations of Electric Resistivity of Mountain Rocks Connected with Tectonic Causes," Tectonophysics, vol. 14, p. 273-277.

Begin, Z. B., 1983, An Approach to the Dating of Young Faults Through the Analysis of Gullies Dissecting Fault Scarps, Publication of Environmental and Hydrogeology Div., Geological Survey of Israel, 13 pp.

Begin, Z. B., D. F. Meyer, and S. A. Schumm, 1981, "Development of Longitudinal Profiles of Alluvial Channels in Response to Base-Level Lowering," Earth Surface Processes and Landforms, vol. 6, p. 49-68.

Bischke, R. E., 1974, "A Model of Convergent Plate Margins Based on Recent Tectonics of Shikoku, Japan," Jour. Geophys. Research, vol. 79, p. 4845-4860.

Blacic, J. D., and J. M. Christie, 1984, "Plasticity and Hydraulic Weakening of Quartz Single Crystals," Jour. Geophys. Research, vol. 89, p. 4223-4239.

Bloom, A. L., W. S. Broecker, J. M. A. Chappell, R. K. Mathews, and K. J. Mesolella, 1974, "Quaternary Sea-Level Fluctuations on a Tectonic Coast: New $^{230}Th/^{234}U$ Dates from the Huon Peninsula, New Guinea," Quaternary Research, vol. 4, p. 185-205.

Bollinger, G. A., 1973, "Seismicity and Crustal Uplift in the Southeastern U.S.," Amer. Jour. Sci., vol. 273-A, p. 396-408.

Bonilla, M. G., and J. M. Buchanan, 1970, Interim Report on World-Wide Historic Surface Faulting, US Geological Survey Open-file Report, 32 pp.

Bonilla, M. G., H. A. Villalobos, and R. E. Wallace, 1984, Exploratory Trench Across the Pleasant Valley Fault, Nevada, Prof. Paper 1274-B, US Geological Survey, p. B1-B14.

Bradley, R. S., 1985, Quaternary Paleoclimatology: Methods of Paleoclimatic Reconstruction, Allen and Unwin, Boston, 472 pp.

Brown, L. D., 1978a, "Prediction of Large-Scale Deformation of the Solid Earth," in National Academy of Science, Geophysical Predictions, Washington, DC, p. 19-28.

Brown, L. D., 1978b, "Recent Vertical Crustal Movements Along the East Coast of the United States," Tectonophysics, vol. 44, p. 205-231.

Brown, L. D., and J. E. Oliver, 1976, "Vertical Crustal Movements from Leveling Data and Their Relation to Geologic Structure in the Eastern United States," Rev. Geophys. Space Phys., vol. 14, p. 13-35.

Brune, J. N., 1968, "Seismic Moment, Seismicity, and Rate of Slip Along Major Fault Zones," Jour. Geophys. Research, vol. 75, p. 777-784.

Bucknam, R. C., and R. E. Anderson, 1979, "Estimation of Fault-Scarp Ages from a Scarp-Height--Slope-Angle Relationship," Geology, vol. 7, p. 11-14.

Bucknam, R. C., S. T. Algermissen, and R. E. Anderson, 1980, "Patterns of Late Quaternary Faulting in Western Utah and an Application in Earthquake Hazard Evaluation," Proceedings, Conference X, Earthquake Hazards Along the Wasatch and Sierra-Nevada Frontal Fault Zones, Open-file Report 80-801, US Geological Survey, p. 299-314.

Bufe, C. G., P. W. Harsh, and R. O. Burford, 1977, "Steady-State Seismic Slip: A Precise Recurrence Model," Geophys. Research Let., vol. 4, p. 91-94.

Bulau, J. R., B. R. Tittman, M. Abdel-Gawad, and C. Salvado, 1984, "The Role of Aqueous Fluids in the Internal Friction of Rock," Jour. Geophys. Research, vol. 89, p. 4207-4211.

Bull, W. B., 1978a, Geomorphic Tectonic Activity Classes of the South Front of the San Gabriel Mountains, California, Unpubl. final report, US Geological Survey Contract 14-08-0001-G-394, 59 pp.

Bull, W. B., 1978b, Tectonic Geomorphology of the Mojave Desert, California, Unpubl. final report, US Geological Survey Contract 14-08-0001-G-394, 188 pp.

Bull, W. B., C. M. Menges, and L. D. McFadden, 1979, Stream Terraces of the San Gabriel Mountains, Southern California, US Geological Survey Final Contract Report 14-08-001-G-394, 100 pp.

Byerlee, J. D., 1968, "Brittle-Ductile Transition in Rocks," Jour. Geophys. Research, vol. 73, p. 6248-6252.

Campbell, D. L., 1978, "Investigation of the Stress-Concentration Mechanism for Intraplate Earthquakes," Geophys. Research Let., vol. 5, p. 477-479.

Carr, W. J., 1974, Summary of Tectonic and Structural Evidence for Stress Orientation at the Nevada Test Site, Open-file Report 74-126, US Geological Survey, 53 pp.

Castle, R. O., J. P. Church, and M. R. Elliot, 1976, "Aseismic Uplift in Southern California," Science, vol. 192, p. 251-254.

Chadwick, O. A., S. Hecker, and J. Fonseca, 1984, A Soils Chronosequence at Terrace Creek: Studies of Late Quaternary Tectonism in Dixie Valley, Nevada, Open-file Report 84-0090, US Geological Survey, 32 pp.

Chappell, J., 1974, "Geology of Coral Terraces, Huon Peninsula, New Guinea: A Study of Quaternary Tectonic Movements and Sea-Level Changes," Geol. Soc. Amer. Bull., vol. 85, p. 553-570.

Chappell, J., and H. H. Veeh, 1978, "Late Quaternary Tectonic Movements and Sea-Level Changes at Timor and Atauro Island," Geol. Soc. Amer. Bull., vol. 89, p. 356-368.

Chapple, W. M., and T. E. Tullis, 1977, "Evaluation of the Forces that Drive the Plates," Jour. Geophys. Research, vol. 82, p. 1967-1984.

Chiburis, E. F., 1981, Seismicity, Recurrence Rates and Regionalization of the Northeastern U.S. and Adjacent Southeastern Canada, NUREG/CR-2309, Nuclear Regulatory Commission, Washington, DC.

Chinnery, M. A., 1979, "An Investigation of Maximum Possible Earthquakes," in US Nuclear Regulatory Commission, Investigations of the Seismological Input to the Safety Design of Nuclear Power Reactors in New England, NUREG/CR-0563, US Nuclear Regulatory Commission, Washington, DC, 67 pp.

Clark, M. M., K. K. Harms, J. J. Leinkaemper, P. S. Harwood, K. R. Lajoie, J. C. Matti, J. A. Perkins, M. J. Rymer, A. M. Sarna-Wojcicki, R. V. Sharp, J. D. Sims, J. C. Tinsley III, and J. I. Ziony, 1984, Preliminary Slip-Rate Table and Map of Late-Quaternary Faults of California, Open-file Report 84-0106, US Geological Survey, 5 sheets, 1:1,000,000 scale, text, 13 pp.

Cluff, L. S., A. S. Patwardhan, and K. J. Coppersmith, 1980, "Estimating the Probability of Occurrences of Surface Faulting Earthquakes on the Wasatch Fault Zone, Utah," Bull. Seismol. Soc. Amer., vol. 70, p. 1463-1478.

Coats, D. W., and R. C. Murray, 1984, Natural Phenomena Hazards Modeling Project: Seismic Hazard Models for DOE Sites," Lawrence Livermore National Laboratories, 85 pp.

Coffman, J. L., and C. A. von Hake, eds., 1973, Earthquake History of the U.S., revised edition (through 1970), National Oceanic and Atmospheric Administration Publication 41-1, 208 pp.

Colman, S. M., and K. L. Pierce, 1979, Preliminary Map Showing Quaternary Deposits and Their Dating Potential in the Conterminous United States, US Geological Survey Miscellaneous Field Studies Map MF-1052 (1 sheet, 1:7,500,000 side).

Colman, S. M., and K. L. Pierce, 1981, Weathering Rinds on Andesitic and Basaltic Stones as a Quaternary Age Indicator, Western United States, Prof. Paper 1210, US Geological Survey, 56 pp.

Colman, S. M., and K. Watson, 1983, "Ages Estimated from a Diffusion Equation Model for Scarp Degradation," Science, vol. 221, p. 263-265.

Coppersmith, K. J., and R. Kulkarni, 1985, "Tectonic Stress Regime and Tectonic Framework of the Eastern United States," in EPRI, Seismic Hazard Methodology for Nuclear Facilities in the United States, Vol. 1, Development of Methodology, Research Project P101-29, Electric Power Research Institute, Palo Alto, CA, p. 3-1--3-61.

Coppersmith, K. J., and D. R. Schwartz, 1984, "Special Section on Fault Behavior and the Earthquake Generation Process," Jour. Geophys. Research, vol. 89, p. 5669-5928.

Corwin, P. F., and H. F. Morrison, 1977, "Self-Potential Variations Preceding Earthquakes in Central California," Geophys. Research Let., vol. 4, p. 171-174.

Cox, J., and P. Talwani, 1984, "Three-Dimensional Description of an Earthquake-Induced Sandblow near Charleston, S. C.," (abstr.), Eos, Trans. Amer. Geophys. Union, vol. 65, p. 241.

Crampin, S., R. Evans, and B. K. Atkinson, 1984, "Earthquake Prediction: A New Physical Basis," Geophys. Jour. Royal Astronom. Soc., vol. 74, p. 147-156.

Cranwell, R. M., and F. A. Donath, 1980, "Application of Geometric Probability to the Existence of Faults in Anistropic Media: Scientific Basis for Nuclear Waste Management," in C. J. M. Northrup, ed., Materials Research Annual.

Crone, A. J., and S. T. Harding, 1984, "Relationship of Late Quaternary Fault Scarps to Subjacent Faults, Eastern Great Basin, Utah," Geology, vol. 12, p. 292-295.

Crone, A. J., and M. N. Machette, 1984, "Surface Faulting Accompanying the Borah Peak Earthquake, Central Idaho," Geology, vol. 12, p. 664-667.

D'Alessandro, M., C. N. Murray, G. Bertozzi, and F. Girardi, 1980, "Probability Analysis of Geological Processes: A Useful Tool for the Safety Assessment of Radioactive Waste Disposal," Radioactive Waste Management (Switzerland), vol. 1, 25-42.

Daowska, R., 1977, "Electromechanical Phenomena Associated with Earthquakes," Geophysical Surveys (Netherlands), vol. 3, p. 157-174.

DeBra, D. B., 1979, "Impact of Technology on Geodesy," in National Academy of Sciences, Studies in Geophysics: Impact of Technology on Geophysics, Washington, DC, p. 22-30.

Dorn, R. I., 1983, "Cation-Ratio Dating: A New Rock Varnish Age-Determination Technique," Quaternary Research, vol. 20, p. 49-73.

Doser, D. I., and R. B. Smith, 1982, "Seismic Moment Rates in the Utah Region," Bull. Seismol. Soc. Amer., vol. 72, p. 525-551.

Ebel, J. E., 1984, "Statistical Aspects of New England Seismicity from 1975 to 1982 and Implications for Past and Future Earthquake Activity," Bull. Seismol. Soc. Amer., vol. 74, p. 1311-1329.

Engdahl, E. R., and C. Kisslinger, 1977, "Seismological Precursors to a Magnitude 5 Earthquake in the Central Aleutian Islands," Jour. Phys. Earth, vol. 25, Suppl., p. S243-S250.

EPRI, 1985, Seismic Hazard Methodology for Nuclear Facilities in the Eastern United States, Vol. 1, Development of Methodology, Research Project P101-29, Electric Power Research Institute, Palo Alto, CA, 235 pp.

Etheridge, M. A., V. J. Wall, and S. F. Cox, 1984, "High Fluid Pressures During Regional Metamorphism and Deformation: Implications for Mass Transport and Deformation Mechanisms," Jour. Geophys. Research, vol. 89, p. 4344-4358.

Evison, F. F., 1977a, "Fluctuations of Seismicity Before Major Earthquakes," Nature, vol. 266, p. 710-712.

Evison, F. F., 1977b, "The Precursory Earthquake Swarm," Phys. Earth Planet. Inter., vol. 15, p. 19-23.

Fedotov, S. A., 1982, "Results of Research on Earthquake Prediction in Kamchatka," Eos, Trans. Amer. Geophys. Union, vol. 63, p. 1260.

Fugro, Inc., 1980, Catalog of World-wide Accelerogram Data, Prepared for Lawrence Livermore Laboratory, April, 1980.

Gable, D., and T. Hatton, 1980, Vertical Crustal Movements in the Conterminous United States Over the Last 10 Million Years, Open-file Report 80-180, US Geological Survey, 9 pp. (extended bibliography, 29 pp., and 4 plates, 1:5,000,000 scale).

Gelfand, I. M., Sh. A. Guberman, M. L. Izvekova, V. I. Keilis-Borok, and E. La. Ranzman, 1972, "Criteria of High Seismicity, Determined by Pattern Recognition," Tectonophysics, vol. 13, p. 415-422.

Geller, R. J., 1976, "Scaling Relations for Earthquake Source Parameters and Magnitude," Bull. Seismol. Soc. Amer., vol. 66, p. 1501-1527.

Geotechnical Engineers, Inc., 1980, State-of-the-Art for Evaluating the Potential Impact of Tectonism and Volcanism on a Radioactive Waste Repository, Geotechnical Engineers, Inc., Winchester, MA.

Goudie, A. S., 1981, "Raised Shorelines," in A. S. Goudie, ed., Geomorphological Techniques, George Allen and Unwin, Ltd., Boston and Sydney, p. 327-341.

Grocott, J., 1977, "The Relationships Between Precambrian Shear Belts and Modern Fault Systems," Jour. Geol. Soc. London, vol. 133, p. 257-262.

Gupta, I. N., 1975, "Premonitory Seismic-Wave Phenomena Before Earthquakes near Fairview Peak, Nevada," Bull. Seismol. Soc. Amer., vol. 65, p. 425-437.

Hadley, J. R., and J. F. Devine, 1974, Seismotectonic Map of the Eastern U.S., Misc. Field Studies Map MF-620, US Geological Survey.

Hagiwara, Y., 1974, "Probability of Earthquake Occurrence as Obtained from a Weibull Distribution Analysis of Crustal Strain," Tectonophysics, vol. 23, p. 313-318.

Hagiwara, Y., 1977, "Gravity Changes Associated with Seismic Activities," Jour. Phys. Earth, vol. 25, Suppl., p. S137-S146.

Hamblin, W. K., P. E. Damon, and W. B. Bull, 1981, "Estimates of Vertical Crustal Strain Rates Along the Western Margins of the Colorado Plateau," Geology, vol. 9, p. 293-298.

Hanks, T. C., and Hiroo Kanamori, 1979, "A Moment Magnitude Scale," Jour. Geophys. Research, vol. 84, p. 2348-2350.

Hanks, T. C., R. C. Bucknam, K. R. Lajoie, and R. E. Wallace, 1984, "Modification of Wave-Cut and Faulting-Controlled Landforms," Jour. Geophys. Research, vol. 89, p. 5771-5790.

Harden, J. W., 1982, "A Quantitative Index of Soil Development from Field Descriptions: Examples from a Chronosequence in Central California," Geoderma, vol. 28, p. 1-28.

Hasegawa, A., T. Hasegawa, and T. Hori, 1975, "Premonitory Variation in Seismic Velocity Related to the Southeastern Akita Earthquake of 1970," Jour. Phys. Earth, vol. 23, p. 189-203.

Holdahl, S. R., and N. L. Morrison, 1974, "Regional Investigation of Vertical Crustal Movements in the U.S., Using Precise Relevelings and Mareograph Data," Tectonophysics, vol. 23, p. 373-390.

Honkura, Y., 1978, "Electrical Conductivity Anomalies in the Earth," Geophys. Survey, vol. 3, p. 225-253.

Housner, G. W., 1969, "Engineering Estimates of Ground Shaking and Maximum Magnitude Earthquakes," Proc. 4th World Conf. Earthquake Engineering, Santiago, Chile.

Howard, K. A., J. M. Aaron, E. E. Brabb, M. R. Brock, H. D. Gower, S. J. Hunt, P. J. Milton, W. R. Muelberger, J. K. Nakata, G. Plafker, D. C. Prowell, R. E. Wallace, and I. J. Watkind, 1978, Preliminary Map of Younger Faults in the United States as a Guide to Possible Fault Activity, US Geological Survey Misc. Field Studies Map MF-916, 2 sheets.

Huang, L., J. McRaney, T. Teng, and M. Prebish, 1979, "A Preliminary Study on the Relationship Between Precipitation and Large Earthquakes in Southern California," Pure Appl. Geophys., vol. 117, p. 1286-1300, Birkhauser Verlag, Basel.

Huber, N. K., 1981, Amount and Timing of Late Cenozoic Uplift and Tilt of the Central Sierra Nevada, California--Evidence from the Upper San Joaquin River Basin, Prof. Paper 1197, US Geological Survey, 28 pp.

Huksson, E., 1981, "Radon Content of Groundwater as an Earthquake Precursor: Evaluation of Worldwide Data and Physical Basis," Jour. Geophys. Research, vol. 86, p. 9397-9410.

Ikeya, M., T. Miki, and K. Tanaka, 1982, "Dating of a Fault by Electron Spin Resonance on Intrafault Materials," Science, vol. 215, p. 1392-1393.

Ishida, M., and H. Kanamori, 1977, "The Spatio-Temporal Variation of Seismicity Before the 1971 San Fernando Earthquake, California," Geophys. Research Let., vol. 4, p. 345-346.

Ishida, M., and H. Kanamori, 1978, "The Foreshock Activities of the 1971 San Fernando Earthquake, California," Bull. Seismol. Soc. Amer., vol. 68, p. 1265-1279.

Jachens, R. C., W. Thatcher, C. W. Roberts, and R. S. Stein, 1983, "Correlation of Changes in Gravity, Elevation, and Strain in Southern California," Science, vol. 219, p. 1215-1217.

Jackson, D. D., W. B. Lee, and C. Liu, 1980, "Aseismic Uplift in Southern California: An Alternative Interpretation," Science, vol. 210, p. 534-536.

Jamison, D. B., and N. G. W. Cook, 1980, "Note on Measured Values for the State of Stress in the Earth's Crust," Jour. Geophys. Research, vol. 85, p. 1833-1838.

Kagan, Ya., and L. Knopoff, 1976, "Statistical Search for Non-Random Features of the Seismicity of Strong Earthquakes," Phys. Earth Planet. Inter., vol. 12, p. 291-318.

Kagan, Ya., and L. Knopoff, 1977, "Earthquake Risk Prediction as a Stochastic Process," Phys. Earth Planet. Inter., vol. 14, p. 97-108.

Kanamori, H., 1981, "The Nature of Seismicity Patterns Before Large Earthquakes," Earthquake Prediction, An International Review, Maurice Ewing Ser., Amer. Geophys. Union, Washington, DC, vol. 4, p. 1-19.

Kanamori, H., and D. L. Anderson, 1975, "Theoretical Basis of Some Empirical Relations in Seismology," Bull. Seismol. Soc. Amer., vol. 65, p. 1073-1106.

Kane, M. F., 1977, "Correlation of Major Eastern Earthquake Centers with Mafic/Ultramafic Basement Masses," Prof. Paper 1028-O, US Geological Survey, p. 199-204.

Keefer, D. K., 1984, "Landslides Caused by Earthquakes," Geol. Soc. Amer. Bull., vol. 94, p. 406-421.

Keller, E. A., M. S. Bonkowski, R. J. Korsch, and R. J. Shlemen, 1982, "Tectonic Geomorphology of the San Andreas Fault Zone in the Southern Indio Hills, Coachella Valley, California," Geol. Soc. Amer. Bull., vol. 93, p. 46-56.

Kerr, R. A., 1979, "Prospects for Earthquake Prediction Wane," Science, vol. 206, p. 542-545.

Keys, W. S., E. Shuter, R. G. Wolff, J. D. Bredehoft, and J. H. Healy, 1979, "In-Situ Measurements Near the San Andreas Fault in Central California," Jour. Geophys. Research, vol. 84, p. 1583-1591.

Kier, S. N., 1984, "Earthquake Prediction from B-Values Discussion," Nature, vol. 310, p. 456.

King, C. Y., 1978, "Radon Emanation on San Andreas Fault," Nature, vol. 271, p. 516-519.

King, J. E., 1978, "New Evidence on the History of the St. Francis Sunk Lands, Northeastern Arkansas," Geol. Soc. Amer. Bull., vol. 89, p. 1719-1722.

Kirby, S. H., 1980, "Tectonic Stresses in the Lithosphere: Constraints Provided by the Experimental Deformation of Rocks," Jour. Geophys. Research, vol. 85, p. 6353-6363.

Kovach, R. L., A. Nur, R. L. Wesson, and R. Robinson, 1975, "Water Level Fluctuations and Earthquakes on the San Andreas Fault Zone," Geology, vol. 3, p. 437-440.

Kronenberg, A. K., and J. Tullis, 1984, "Flow Strengths of Quartz Aggregates: Grain Size and Pressure Effects due to Hydrolytic Weakening," Jour. Geophys. Research, vol. 89, p. 4281-4297.

Langbein, J. O., M. F. Linker, A. McGarr, R. C. Jachens, and L. E. Slater, 1983, "Two-color Geodimeter Measurements of Crustal Strain Accumulation near Palmdale, California: Comparisons with Gravity and Meteorological Data," Eos. Trans. Amer. Geophys. Union, vol. 64, p. 841.

Latynina, L. A., and S. D. Rizaeva, 1976, "On Tidal-Strain Variations Before Earthquakes," Tectonophysics, vol. 31, p. 121-127.

Lensen, G. J., 1964, "The General Case of Progressive Fault Displacement of Flights of Degradational Terraces," New Zealand Jour. Geol. and Geophys., vol. 7, p. 861-870.

Lensen, G. J., 1968, "Analysis of Progressive Fault Displacement During Downcutting at the Branch River Terraces, South Island, New Zealand," Geol. Soc. Amer. Bull., vol. 79, p. 545-556.

Lindh, A., G. Fuis, and C. Mantis, 1978, "Seismic Amplitude Measurements Suggest Foreshocks Have Different Focal Mechanism Than Aftershocks," Science, vol. 201, p. 56-59.

Lisitzin, E., 1974, Sea-Level Changes, Elsevier Oceanography Series, No. 8, Elsevier, Amsterdam, Holland, 286 pp.

Liu, H. S., 1980, "Mantle Convection and Subcrustal Stresses Under the United States," Modd. Geol., vol. 7, p. 81-93.

Locke, W. W., J. T. Andrews, and P. J. Webber, 1979, "A Manual for Licheno-metry," Technical Bull. 26, British Geomorphological Research Group, Norwich, Univ. of East Anglia.

Lucchitta, I., 1979, "Late Cenozoic Uplift of the Southwestern Colorado Plateau and Adjacent Lower Colorado River Region," Tectonophysics, vol. 61, p. 63-95.

Machette, M. N., 1978, "Dating Quaternary Faults in the Southwestern United States by Using Buried Calcic Paleosols," US Geological Survey Jour. Research, vol. 6, p. 369-381.

Machette, M. N., 1982, Soil Dating Techniques, Western Region (United States), Open-file Report OFR-82-840, US Geological Survey, p. 137-140.

Machette, M. N., and R. G. McGimsey, 1982, Quaternary and Pliocene Faults in the Socorro and Western Part of the Fort Sumner 1° x 2° Quadrangles, New Mexico, US Geological Survey Miscellaneous Field Studies Map MF-1465-A (1 sheet, scale 1:250,000, with explanatory text, 12 pp.).

Machette, M. N., and S. E. Personius, 1984, Map of Quaternary and Pliocene Faults in the Eastern Part of the Aztec 1° x 2° Quadrangle and the Western Part of the Raton 1° x 2° Quadrangle, Northern New Mexico, US Geological Survey Miscellaneous Field Studies Map MF-1465-B (Scale 1:250,000, with text, 14 pp.).

Mallio, W. J., and J. H. Peck, 1981, "Practical Aspects of Geological Prediction," Bull. Assoc. Engineering Geologists, vol. 18, p. 369-374.

Mark, R. K., 1977, "Application of Linear Statistical Models of Earthquake Magnitude Versus Fault Length in Estimating Maximum Expectable Earth-quakes," Geology, vol. 5, p. 464-466.

Mark, R. K., J. C. Tinsley, E. B. Newman, T. D. Gilmore, and R. O. Castle, 1981, "An Assessment of the Accuracy of the Geodetic Measurements that Led to the Recognition of the Southern California Uplift," Jour. Geophys. Research, vol. 86, p. 2783-2808.

Matsuda, T., Y. Ota, M. Ando, and N. Yonekura, 1978, "Fault Mechanism and Recurrence Time of Major Earthquakes in Southern Kanto District, Japan, as Deduced from Coastal Terrace Data," Geol. Soc. Amer. Bull., vol. 89, p. 1610-1618.

Matti, J. C., J. C. Tinsley, D. M. Morton, and L. D. McFadden, 1982, "Holocene Faulting History as Recorded by Alluvial Stratigraphy Within the Cucamonga Fault Zone: A Preliminary View," in J. C. Tinsley, J. C. Matti, and L. D. McFadden, eds., Guidebook, Field Trip No. 12, Geol. Soc. Amer., Cordillera Section, p. 29-44.

Mayer, Larry, 1979, "Evolution of the Mogollon Rim in Central Arizona," Tectonophysics, vol. 61, p. 49-62.

Mayer, Larry, 1982, Quantitative Tectonic Geomorphology, with Applications to Neotectonics of Northwestern Arizona, Ph.D. Thesis, Univ. of Arizona, Tucson, AZ, 512 pp.

Mayer, Larry, 1984, "Dating Quaternary Fault Scarps Formed in Alluvium Using Morphological Parameters," Quaternary Research, vol. 22, p. 300-313.

Mayer, Larry, M. Mergner-Keefer, and C. M. Wentworth, 1981, Probability Models and Computer Simulation of Landscape Evolution, US Geological Survey Open-file Report OFR-81-656, 37 pp.

McCalpin, J. P., 1982, "Quaternary Geology and Neotectonics of the West Flank of the Northern Sangre de Cristo Mountains, South-Central Colorado," Colorado School of Mines Quarterly, vol. 77, 97 pp.

McCann, W. R., S. P. Nishenko, L. R. Sykes, and J. Krause, 1978, "Seismic Gaps and Plate Tectonics: Seismic Potential for Major Plate Boundaries," in J. F. Evernden (Convener), B. L. Isacks and G. Plafker (Organizers), Proc. Conf. VI Methodology for Identifying Seismic Gaps, Open-file Report 78-943, US Geological Survey, p. 441-584.

McFadden, L. D., and J. C. Tinsley, 1982, "Soil Profile Development in Xeric Climates: A Summary," in J. C. Tinsley, J. C. Matti, and L. D. McFadden, eds., Guidebook, Field Trip No. 12, Geol. Soc. Amer., Cordillera Section, p. 15-19.

McGarr, A., 1984, "Scaling of Ground Motion Parameters, State of Stress and Focal Depth, Jour. Geophys. Research, vol. 89, p. 6969-6979.

McGarr, A., and N. C. Gay, 1978, "State of Stress in the Earth's Crust," Ann. Rev. Earth Planet. Sci., vol. 6, p. 405-436.

McGarr, A., M. D. Zoback, and T. C. Hanks, 1982, "Implications of an Elastic Analysis of In-Situ Stress Measurements Near the San Andreas Fault," Jour. Geophys. Research, vol. 88, p. 2213-2219.

McGuire, R. K., 1977, "Effects of Uncertainty in Seismicity on Estimates of Seismic Hazard on the East Coast of the United States," Bull. Seismol. Soc. Amer., vol. 67, p. 827-898.

McLaughlin, R. J., K. R. Lajoie, D. H. Sorg, S. D. Morrison, and J. A. Wolfe, 1983, "Tectonic Uplift of a Middle Wisconsin Marine Platform near the Mendocino Triple Junction, California," Geology, vol. 11, p. 35-39.

Merifield, P. M., and D. L. Lamar, 1981, "Anomalous Water-Level Changes and Possible Relation with Earthquakes," Eos, Trans. Amer. Geophys. Union, vol. 62, p. 1034.

Mikumo, T., M. Kato, H. Doi, Y. Wada, and T. Tanaka, 1977, "Possibility of Temporal Variations in Earth Tidal Strain Amplitudes Associated with Major Earthquakes," Jour. Phys. Earth, vol. 25, Suppl., p. S123-S136.

Mogi, K., 1968, "Sequential Occurrences of Recent Great Earthquakes," Jour. Phys. Earth, vol. 16, p. 30-36.

Morrison, H. F., R. Fernandez, and R. F. Corwin, 1979, "Earth Resistivity, Self Potential Variations, and Earthquakes: A Negative Result for M = 4.0," Geophys. Research Let., vol. 6, p. 139-142.

Moyle, W. R., Jr., 1980, Groundwater-Level Monitoring for Earthquake Prediction. A Progress Report Based on Data Collected in Southern California, 1976-1979, Open-file Report 80-413, US Geological Survey, 60 pp.

Muhs, D. R., and B. J. Szabo, 1982, "Uranium-Series Age of the Eel Point Terrace, San Clemente Island, California," Geology, vol. 10, p. 23-26.

Nansen, G. C., 1980, "A Regional Trend to Meander Migration," Jour. Geology, vol. 88, p. 100-108.

NASA, 1979, Application of Space Technology to Crustal Dynamics and Earthquake Research, Tech. Paper 1464, National Aeronautics and Space Administration, Washington, DC, 257 pp.

Nash, D. B., 1980, "Morphologic Dating of Degraded Normal Fault Scarps," Jour. Geology, vol. 88, p. 353-360.

Nash, D. B., 1984, "Morphologic Dating of Fluvial Terrace Scarps and Fault Scarps Near West Yellowstone, Montana," Geol. Soc. Amer. Bull., vol. 95, p. 1413-1424.

Negmatullayev, S. K., K. M. Mirzoyev, O. V. Soboleva, A. S. Malamud, V. I. Starkov, R. S. Mihailova, M. V. Kulagina, and E. Y. Starkova, 1984, "Activation of the Seismic Processes in Regional Structures of the Lithosphere and a New Approach to the Problem of Long-Term Earthquake Prediction," in S. A. Fedotov, I. N. Galkin, A. V. Nikolayev, and E. N. Sedova, eds., Earthquakes and Geological Hazard Prediction, Internat. Geol. Congress, vol. 27, p. 34-44.

Niazi, M., and C. P. Mortgat, 1984, "Application of Logistic Models to Earthquake Forecasting," Earthquake Prediction Research, vol. 2, p. 221-225.

NOAA, no date, "Digitized Strong Motion Data Tapes and Intensity File Tapes," World Data Center A, National Oceanic and Atmospheric Administration, Washington, DC.

Noritomi, K., 1978, "Application of Precursory Geoelectric and Geomagnetic Phenomena to Earthquake Prediction in China," Chin. Geophys. (Amer. Geophys. Union), vol. 1, p. 377-391.

Nuttli, O. W., 1974, "Magnitude-Recurrence Relation for Central Mississippi Valley Earthquakes," Bull. Seismol. Soc. Amer., vol. 64, p. 1189-1207.

Nuttli, O. W., 1983a, "Average Seismic Source--Parameter Relations for Mid-Plate Earthquakes," Bull. Seismol. Soc. Amer., vol. 73, p. 519-535.

Nuttli, O. W., 1983b, "Empirical Magnitude and Spectral Scaling Relations for Mid-Plate and Plate-Margin Earthquakes," Tectonophysics, vol. 93, p. 207-223.

Obermeier, S. F., G. S. Gohn, R. E. Weems, R. L. Gelinkas, and M. Rubin, 1985, "Geologic Evidence for Recurrent Moderate to Large Earthquakes Near Charleston, South Carolina," Science, vol. 227, p. 408-411.

Ohtake, M., 1976, "Search for Precursors of the 1974 Izu-Hanto-Oki Earthquake, Japan," Pure Appl. Geophys., vol. 114, p. 1083-1093.

Ohtake, M., T. Matumoto, and G. V. Latham, 1977, "Seismicity Gap near Oaxaca Southern Mexico as a Probable Precursor to a Large Earthquake," Pure Appl. Geophys., vol. 115, p. 375-385.

Ohtake, M., T. Matumoto, and G. V. Latham, 1978, "Patterns of Seismicity Preceding Earthquakes in Central America, Mexico and California," in J. F. Evernden (Convener), B. L. Isacks and G. Plafker (Organizers), Proc. Conf. VI Methodology for Identifying Seismic Gaps, Open-file Report 78-943, US Geological Survey, p. 585-610.

Oliver, J., and L. Murphy, 1971, "WWSSN: Seismology's Global Network of Observing Stations," (World Wide Standardized Seismograph Network) Science, vol. 174, p. 267-274.

O'Neill, J. R., and T. C. Hanks, 1980, "Geochemical Evidence for Water-Rock Interaction Along the San Andreas and Garlock Faults of California," Jour. Geophys. Research, vol. 85, p. 6286-6292.

Ota, Y., 1975, "Late Quaternary Vertical Movement in Japan Estimated From Deformed Shorelines," Bull. Research Soc. New Zealand, vol. 13, p. 231-239.

Ouchi, Shanji, 1985, "Response of Alluvial Rivers to Slow Active Tectonic Movement," Geol. Soc. Amer. Bull., vol. 96, p. 504-515.

Page, R., 1970, "Dating Episodes of Faulting From Tree Rings: Effects of the 1958 Rupture of the Fairweather Fault on Tree Growth," Geol. Soc. Amer. Bull., vol. 81, p. 3085-3094.

Passchier, C. W., 1982, "Pseudotachylyte and the Development of Ultramylorite Bands in the Saint-Barthelemy Massif, French Pyrenees," Jour. Structural Geology, vol. 4, p. 69-79.

Pearthree, P. A., and S. S. Calvo, 1982, Late Quaternary Faulting West of the Santa Rita Mountains South of Tucson, Arizona, M.S. Thesis, Univ. of Arizona, Tucson, AZ, 49 pp.

Pearthree, P. A., C. M. Menges, and Larry Mayer, 1983, Distribution, Recurrence, and Possible Tectonic Implications of Late Quaternary Faulting in Arizona, Open-file Report 83-20, Arizona Bureau of Geology and Mineral Technology, 51 pp.

Pillans, B., 1983, "Upper Quaternary Marine Terrace Chronology and Deformation, South Taranaki, New Zealand," Geology, vol. 11, p. 292-297.

Plafker, G., and M. Rubin, 1978, Uplift History and Earthquake Recurrence as Deduced from Marine Terraces on Middleton Island, Alaska, Open-file Report 78-9434, US Geological Survey, p. 687-721.

Poppe, B. B., 1979, "Historical Survey of U.S. Seismograph Stations," Prof. Paper 1096, US Geological Survey, 129 pp.

Powers, D. W., S. J. Lambert, S. Shaffer, L. R. Hill, and W. D. Weart, eds., 1978, Geological Characterization Report, Waste Isolation Pilot Plant (WIPP) Site, Southeastern New Mexico, SAND78-1596, Sandia National Laboratories, Albuquerque, New Mexico, 2 vols.

Prescott, W. H., J. C. Savage, and W. T. Kinoshita, 1979, "Strain Accumulation Rates in the Western U.S. Between 1970 and 1978," Jour. Geophys. Research, vol. 84, p. 5423-5435.

Purcarn, G., and H. Berkhemer, 1982, "Quantitative Relations of Seismic Source Parameters and a Classification of Earthquakes," Tectonophysics, vol. 84, p. 57-128.

Raleigh, B., G. Bennet, H. Craig, T. Hanks, P. Molnar, A. Nur, J. Savage, C. Scholz, R. Turner, and F. Wu, 1977, "Prediction of the Haicheng Earthquake," Eos. Trans. Amer. Geophys. Union, vol. 58, p. 236-272.

Ratcliff, N. M., 1983, "Fault Reactivation Models for the Origin of Eastern U.S. Seismicity," Proc. Conf. XX, Open-file Report 83-843, US Geological Survey, p. 137-141.

Reches, Z., 1983, "Faulting of Rocks in Three-Dimensional Strain Field. II. Theoretical Analysis," Tectonophysics, vol. 95, p. 133-156.

Reddy, D. P., ed., 1983, Seismic Design Technology for Breeder Reactor Structures, Vol. 1. Special Topics in Earthquake Ground Motion, Agbabian Associates, El Segundo, CA, 267 pp.

Reed, J. C., Jr., 1981, "Disequilibrium Profile of the Potomac River Near Washington, D.C.--A Result of Lowered Base Level or Quaternary Tectonics Along the Fall Line?" Geology, vol. 9, p. 445-450.

Reilinger, R., M. Bevis, and G. Jurkowski, 1984, "Tilt from Releveling: An Overview of the U.S. Data Base," Tectonophysics, vol. 107, p. 315-330.

Rhoades, D. A., and F. F. Evison, 1979, "Long-Term Earthquake Forecasting Based on a Single Predictor," Geophys. Jour. Royal Astronom. Soc., vol. 59, p. 43-46.

Richardson, R. M., S. C. Solomon, and N. H. Sleep, 1979, "Tectonic Stress in the Plates," Rev. Geophys. Space Phys., vol. 17, p. 981-1019.

Riecker, R. E., ed., 1979, Rio Grande Rift--Tectonics and Magmatism, Amer. Geophys. Union., Washington, DC, 438 pp.

Rikitake, T., 1974, "Probability of Earthquake Occurrence as Estimated From Crustal Strain," Tectonophysics, vol. 23, p. 299-312.

Rikitake, T., 1975a, "Earthquake Precursors," Bull. Seismol. Soc. Amer., vol. 65, p. 1133-1162.

Rikitake, T., 1975b, "Statistics of Ultimate Strain of the Earth's Crust and Probability of Earthquake Occurrence," Tectonophysics, vol. 26, p. 1-21.

Rikitake, T., 1976, Earthquake Prediction, Elsevier, Amsterdam, 357 pp.

Rikitake, T., 1979a, "Changes in the Direction of Magnetic Vector of Short-Period Geomagnetic Variations Before the 1972 Sitka, Alaska, Earthquake," Jour. Geomag. Geoelectr., vol. 31, p. 441-448.

Rikitake, T., 1979b, "Classification of Earthquake Precursors," Tectonophysics, vol. 54, p. 293-309.

Rikitake, T., 1982, Earthquake Forecasting and Warning, Center for Academic Publications, Tokyo, D. Reidel Publ. Co., Dordrecht, Holland, 403 pp.

Rikitake, T., 1984, "Active Fault and Crustal Strain," Earthquake Prediction Research, vol. 2, p. 167-189.

Rockwell, T. K., E. A. Keller, M. N. Clark, and D. L. Johnson, 1984, "Chronology and Rates of Faulting of Ventura River Terraces, California," Geol. Soc. Amer. Bull., vol. 95, p. 1466-1474.

Rothe, J. P., 1972, The Seismicity of the Earth (1953-1965), UNESCO, New York, 336 pp.

Russ, D. P., 1982, "Style and Significance of Surface Deformation in the Vicinity of New Madrid, Mo.," in F. A. McKeown and L. C. Pakiser, eds., Investigation of the New Madrid, Mo., Earthquake Region, Prof. Paper 1286, US Geological Survey, p. 95-114.

Ryall, A., D. B. Slemmons, and L. D. Gedney, 1966, "Seismicity, Tectonism, and Surface Faulting in the Western United States During Historic Time," Bull. Seismol. Soc. Amer., vol. 56, p. 1105-1135.

Sato, H., 1977, "Some Precursors Prior to Recent Great Earthquakes Along the Nankai Trough," Jour. Phys. Earth, vol. 25, Suppl., p. S115-S121.

Sauber, J., K. McNally, J. C. Pechmann, and H. Kanamori, 1983, "Seismicity Near Palmdale, California, and Its Relation to Strain Changes," Jour. Geophys. Research, vol. 88, p. 2213-2219.

Savage, J. C., 1972, "Relation of Corner Frequency to Fault Dimensions," Jour. Geophys. Research, vol. 77, p. 3788-3795.

Savage, J. C., and L. M. Hastie, 1966, "Surface Deformation Associated with Dip-Slip Faulting," Jour. Geophys. Research, vol. 71, p. 4897-4906.

Schwartz, D. P., and K. J. Coppersmith, 1984, "Fault Behavior and Characteristic Earthquakes: Examples From the Wasatch and San Andreas Fault Zones," Jour. Geophys. Research, vol. 89, p. 5681-5698.

Segall, P., 1984, "Rate-Dependent Extensional Deformation Resulting From Crack Growth in Rock," Jour. Geophys. Res., vol. 89, p. 4185-4195.

Segall, P., and D. D. Pollard, 1980, "Mechanics of Discontinuous Faults," Jour. Geophys. Research, vol. 85, p. 4337-4350.

Sekiya, H., 1977, "Anomalous Seismic Activity and Earthquake Prediction," Jour. Phys. Earth, vol. 25, Suppl., p. S85-S93.

Self, S., and R. J. S. Sparks, eds., 1981, "Tephra Studies," Proc. NATO Advanced Studies Institute, Tephra Studies as a Tool in Quaternary Research, D. Reidel Publ. Co., Dordrecht, Holland.

Semyenov, A. N., 1969, "Variations in the Travel Time of Transverse and Longitudinal Wave Before Violent Earthquakes," Izv. Acad. Sci. USSR (Phys. Solid Earth) (English edition), vol. 4, p. 245-248.

Sexton, J. L., W. J. Hinze, R. R. B. von Frese, and L. W. Braile, 1982, "Long-Wavelength Aeromagnetic Anomaly Map of the Conterminous United States," Geology, vol. 10, p. 364-369.

Shannon & Wilson/Agbabian Associates, 1976, Geotechnical and Strong Motion Earthquake Data From U.S. Accelerograph Stations, NUREG-0029, US Nuclear Regulatory Commission, Washington, DC, 3 Vols.

Shaw, H. R., and A. E. Gartner, 1984, Empirical Laws of Order Among Rivers, Faults, and Earthquakes, Open-file Report 84-0356, US Geological Survey, 55 pp.

Sheets, P. D., and D. K. Grayson, eds., 1979, Volcanic Activity and Human Ecology, Academic Press, New York.

Shimamura, H., 1982, "Microtemperature Measurements of Groundwater in Earthquake Impending Areas in Japan," Eos, Trans. Amer. Geophys. Union, vol. 63, p. 1260.

Shimazaki, K., and T. Nakata, 1980, "Time-Predictable Recurrence Model for Large Earthquakes," Geophys. Research Let., vol. 7, p. 279-282.

Sibson, R. H., 1977, "Fault Rocks and Fault Mechanisms," Jour. Geol. Soc. London, vol. 133, p. 191-214.

Sibson, R. H., 1981, "Fluid Flow Accompanying Faulting: Field Evidence and Models," in D. W. Simpson and P. G. Richards, eds., Earthquake Prediction: An International Review, M. Ewing Series, vol. 4, Amer. Geophys. Union, p. 593-604.

Sibson, R. H., 1983, "Continental Fault Structure and the Shallow Earthquake Source," Jour. Geol. Soc. London, vol. 140, p. 741-767.

Sibson, R. H., 1984, "Roughness at the Base of the Seismographic Zone: Contributing Factors," Jour. Geophys. Research, vol. 89, p. 5794-5799.

Sieh, K. E., 1978a, "Prehistoric Large Earthquakes Produced by Slip on the San Andreas Fault at Pallett Creek, California," Jour. Geophys. Research, vol. 83, p. 3907-3939.

Sieh, K. E., 1978b, "Slip Along the San Andreas Fault Associated with the Great 1857 Earthquake," Bull. Seismol. Soc. Amer., vol. 68, p. 1421-1448.

Sieh, K. E., 1984, "Lateral Offsets and Revised Dates of Prehistoric Earthquakes at Pallett Creek, Southern California," Jour. Geophys. Research, vol. 89, no. B9, p. 7641-7670.

Sieh, K. E., and R. H. Jahns, 1984, "Holocene Activity of the San Andreas Fault at Wallace Creek, California," Geol. Soc. Amer. Bull., vol. 95, p. 883-896.

Simpson, D. W., and P. G. Richards, eds., 1981, Earthquake Prediction: An International Review, M. Ewing Series, vol. 4, Amer. Geophys. Union, 680 p.

Slemmons, D. B., 1982, "Determination of Design Earthquake Magnitudes for Micro-Zonation," Proc. Third Internat. Microzonation Conf., vol. 1, p. 119-130.

Smith, B. E., and M. J. S. Johnston, 1976, "A Tectonomagnetic Effect Observed Before a Magnitude 5.2 Earthquake Near Hollister, California," Jour. Geophys. Research, vol. 81, p. 3556-3560.

Smith, R. B., 1977, "Intraplate Tectonics of the Western North American Plate," Tectonophysics, vol. 37, p. 323-336.

Smith, R. B., and R. L. Bruhn, 1984, "Intraplate Extensional Tectonics of the Eastern Basin-Range: Inferences on Structural Style from Seismic Reflection Data, Regional Tectonics, and Thermo-Mechanical Models of Brittle-Ductile Deformation," Jour. Geophys. Research, vol. 89, p. 5733-5762.

Stepp, J. C., 1972, "Analysis of Completeness of the Earthquake Sample in the Puget Sound Area and Its Effect on Statistical Estimates of Earthquake Hazard," Proc. Internat. Conf. Microzonation, vol. 2, p. 897-910.

Stepp, J. C., W. A. Rinehart, and S. T. Algermissen, 1965, Earthquakes in the United States 1963-64 and an Evaluation of the Detection Capability of the U.S. Seismograph Stations, US Coast and Geodetic Survey, ARPA Order 620.

Stevens, A. E., 1980, "History of Some Canadian and Adjacent American Seismograph Stations," Bull. Seismol. Soc. Amer., vol. 70, p. 1381-1393.

Suggate, R. P., 1960, "The Interpretation of Progressive Fault Displacement of Flights of Terraces," New Zealand Jour. Geol. and Geophys., vol. 3, p. 364-374.

Swan, F. H., III, D. P. Schwartz, and L. S. Cluff, 1980, "Recurrence of Moderate to Large Magnitude Earthquakes Produced by Surface Faulting on the Wasatch Fault Zone," Bull. Seismol. Soc. Amer., vol. 70, p. 1431-1462.

Swanberg, C. A., and P. Morgan, 1978, "The Linear Relationship Between Temperatures Based on the Silica Content of Groundwater and Regional Heat Flow: A New Heat Flow Map of the U.S.," Pure Appl. Geophys., vol. 177, p. 227-241.

Swanson, P. L., 1984, "Subcritical Crack Growth and Other Time- and Environment-Dependent Behavior in Crustal Rocks," Jour. Geophys. Res., vol. 89, p. 4137-4152.

Sykes, L. R., 1971, "Aftershock Zones of Great Earthquakes, Seismicity Gaps, and Earthquake Prediction for Alaska and the Aleutians," Jour. Geophys. Research, vol. 76, p. 8021-8041.

Sykes, L. R., 1978, "Intraplate Seismicity, Reactivation of Pre-Existing Zones of Weakness, Alkaline Magmatism, and Other Tectonism Postdating Continental Fragmentation," Rev. Geophys. Space Phys., vol. 16, p. 621-688.

Tagutschi, Y., and others, 1983, The Interpretation of Changes in Ground Water Level Caused by Earthquakes, Open-file Report 80-108, US Geological Survey.

Tocher, Don, 1958, "Earthquake Energy and Ground Breakage," Bull. Seismol. Soc. Amer., vol. 48, p. 147-153.

Turcotte, D. L., and G. Schubert, 1982, Geodynamics: Applications of Continuum Physics to Geological Problems, John Wiley & Sons, New York, 450 pp.

US Geological Survey, 1980, Proceedings of Conference X, Earthquake Hazards Along the Wasatch and Sierra-Nevada Frontal Fault Zones, Open-File Report 80-801, US Geological Survey, Menlo Park, CA, 600 pp.

Varotsos, P., and K. Alexopoulos, 1984, "Physical Properties of the Variations of the Electrical Field of the Earth Preceeding Earthquakes; I," Tectonophysics, vol. 110, p. 73-98.

Veneziano, D., and K. Coppersmith, 1985, "Estimation of Seismicity Parameters," in EPRI, Seismic Hazard Methodology for Nuclear Facilities in the Eastern United States, Vol. 1, Development of Methodology, Research Project P101-29, Electric Power Research Institute, Palo Alto, CA, p. 5-1 to 5-37.

Veneziano, D., C. A. Cornell, and T. O'Hara, 1983, "Historical Seismic Hazard Analysis," Proc. Seismic Risk and Heavy Industrial Facilities Conf., San Francisco, May 11, 1983.

Vere-Jones, D., 1978, "Earthquake Prediction--A Statistician's View," Jour. Phys. Earth, vol. 26, p. 129-146.

Von Seggern, D. H., 1982, Investigation of Seismic Precursors Before Major Earthquakes and the State of Stress on Fault Planes, Ph.D. Thesis, Pennsylvania State Univ., University Park, PA, 352 pp.

Wallace, R. E., 1977, "Profiles and Ages of Young Fault Scarps, North-Central Nevada," Geol. Soc. Amer. Bull., vol. 88, p. 1267-1281.

Wallace, R. E., 1980, "Discussion--Nomographs for Estimating Components of Fault Displacement From Measured Height of Fault Scarp," Bull. Assoc. Engineering Geologists, vol. 17, p. 39-45.

Wallace, R. E., 1981, Active Faults, Paleoseismology, and Earthquake Hazards: Earthquake Prediction--An International Review, Maurice Ewing Series 4, Amer. Geophys. Union, p. 209-216.

Ward, P. L., 1978, "Earthquake Prediction," in National Academy of Sciences, Geophysical Predictions, National Academy of Sciences, Washington, DC, p. 37-46.

Watts, M. J., and G. D. Williams, 1979, "Fault Rocks as Indicators of Progressive Shear Deformation in the Guingamp Region, Britanny," Jour. Structural Geology, vol. 1, p. 323-332.

Weldon, R. J., III, and K. E. Sieh, 1985, "Holocene Rate of Slip and Tentative Recurrance Interval for Large Earthquakes on the San Andreas Fault, Cajon Pass, Southern California," Geol. Soc. Amer. Bull., vol. 96, p. 793-812.

Wentworth, C. M., and M. Mergner-Keefer, 1983, "Regenerate Faults of Small Cenozoic Offset--Probable Earthquake Concern in the Southeastern United States," Prof. Paper 1313, US Geological Survey, p. 51-520.

Wesson, R. L., 1981, "Interpretation of Changes in Water Level Accompanying Fault Creep and Implications for Earthquake Prediction," Jour. Geophys. Research, vol. 86, p. 9259-9267.

Williams, T. R., 1982, Late Pleistocene Lake Level Maxima and Shoreline Deformation in the Basin and Range Province, Western United States, M.S. Thesis, Colorado State Univ., Fort Collins, CO, 52 pp. (1 plate, 1:2,500,000 scale).

Wyss, M., 1975, "A Search for Precursors to the Sitka, 1972, Earthquake: Sea Level, Magnetic Field, and P-Residuals," Pure Appl. Geophys., vol. 113, p. 297-309.

Wyss, M., 1976a, "Local Changes of Sea Level Before Large Earthquakes in South America," Bull. Seismol. Soc. Amer., vol. 66, p. 903-914.

Wyss, M., 1976b, "Local Sea Level Changes Before and After the Hyuganada, Japan, Earthquakes of 1961 and 1968," Jour. Geophys. Research, vol. 81, p. 5315-5321.

Wyss, M., 1977, "The Appearance Rate of Premonitory Uplift," Bull. Seismol. Soc. Amer., vol. 67, p. 1091-1098.

Wyss, M., 1981, "Recent Earthquake Prediction Research in the United States," in T. Rikitake, ed., Current Research in Earthquake Prediction I, Center for Academic Publications Japan, D. Reidel Publ. Co., Tokyo, p. 81-127.

Yamazaki, Y., 1975, "Precursory and Coseismic Resistivity Changes," Pure Appl. Geophys., vol. 113, p. 219-227.

Yamazaki, Y., 1977, "Tectonoelectricity," Geophysical Surveys (Netherlands), vol. 3, p. 123-142.

Youd, T. L., and D. K. Keefer, 1985, "Landslides Caused by Earthquakes: Discussion and Reply," Geol. Soc. Amer. Bull., vol. 96, p. 1091-1094.

Youd, T. L., and D. M. Perkins, 1978, "Mapping of Liquifaction-Induced Ground Failure Potential," Amer. Soc. Engineers, Jour. Geotechnical Engineering Div., vol. 104, no. GT4, p. 433-446.

Zellmer, J. T., G. R. Roquemore, and B. A. Blackerby, 1985, "Modern Tectonic Cracking Near the Garlock Fault, California," Geol. Soc. Amer. Bull., vol. 96, p. 1037-1042.

Ziony, J. I., C. M. Wentworth, J. M. Buchanan-Banks, and H. C. Wagner, 1974, Preliminary Map Showing Recency of Faulting in Coastal Southern California, Miscellaneous Field Investigations Map MF-585, US Geological Survey, (3 sheets, 1:250,000 scale, with explanatory text, 15 pp.).

Zoback, M. D., 1983, "Intraplate Earthquakes, Crustal Deformation, and In-Situ Stress," Proc. Conference XX, Open-file Report 83-843, p. 169-179.

Zoback, M. L., and M. D. Zoback, 1980, "State of Stress in the Conterminous United States," Jour. Geophys. Research, vol. 85, p. 6113-6156.

Chapter 5

SEISMIC HAZARD ASSESSMENT*

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Abstract

The quantitative assessment of seismic hazard at a site includes both probabilistic predictions and uncertainty statements. The former result from an integration of a stochastic earthquake recurrence model (generally, future times, locations, and source parameter values) and a probabilistic site-effects prediction model (ground shaking and/or faulting). Hazard uncertainty statements result from explicit propagation of parameter and model uncertainty through the hazard calculations. Methods for these analyses are straightforward and widely applied in current practice. This chapter therefore focuses on the two major elements: recurrence models and site-effect prediction models.

Current hazard practice, which is applicable at least to the operational phase of a repository, is based almost solely on the the memoryless Poissonian earthquake recurrence model. Its data needs are relatively limited, although low-hazard, long-time-window estimates will be subject to significant, if quantifiable, uncertainty. Adequacy of this Poisson model for long-window hazard predictions has not yet been well investigated. Questions of seismicity stationarity become more dominant in the long-window case; non-stationary and/or stochastically changing parameter values have not been well studied or applied.

Non-Poissonian models of earthquake recurrence are also reviewed. Characteristic magnitudes, characteristic inter-event times, earthquake "cycles," stochastic dependencies between inter-event times and magnitudes, and temporal and spatial memory have all been modelled. They parallel the scientific developments in the geosciences, Chapter 4. Their data needs are much more intense than Poisson models'. Practical experience is negligible.

Site-effect prediction models are separated into two major categories: ground shaking and faulting. Ground-motion prediction models estimate (probabilistically) important characteristics of the motion at a site some distance from an event of specified source characteristics. Current methods include

*This chapter reviews and evaluates techniques for assigning probabilities to future seismic hazards. This review and evaluation does not imply that the NRC has endorsed the use of the techniques discussed.

direct and indirect empirical methods as well as more recent semi-empirical, stochastic, and deterministic methods. This sequence of models involves an increasingly stronger physical basis, increasing instrumental data requirements, and often increasingly more parameters and/or independent (source and site) variables. All these estimators display large prediction variability. Current development, however, is rapid. This chapter also reviews the less common prediction of ground motions at depth viz-a-viz those at the surface.

Site-faulting prediction models are categorized as "magnitude-occurrence" and "faulting-occurrence" models. The former are more closely analogous to ground-motion prediction models; the latter do not use earthquake magnitude as an intermediate variable. These prediction models are all probabilistic and strongly empirical.

Seismic Hazard Integration

The probabilistic analysis of the threat of seismological effects at a site requires an integration of two basic elements. The first is a general earthquake recurrence model: a probabilistic prediction of future earthquake dates, locations, and source characteristics (magnitude, rupture length, etc.). The second element is a probabilistic prediction of the effects at the site given the location and source characteristics of an event. The site effects of interest may include one or more measures of strong ground motion and/or faulting. This chapter describes the current status of these various elements.

The integration of the recurrence and site-effects models into a site hazard assessment is straightforward and therefore does not deserve extensive treatment here. While there may be differences in computational details, all such integration procedures involve an application of the total probability theorem, which states that the probability of event A is the sum of a set of products. Each term of the sum is a product of two factors: (1) the conditional probability of A given the occurrence of some event B_i and (2) the probability of B_i. The sum is over all possible events B_i (the B_i's are a mutually exclusive, exhaustive set). In the current application, event A is the site-effect hazard statement of interest (e.g., the peak ground acceleration exceeds 0.5 g at least once in the next T years). Its conditional probability can be obtained from the probabilistic site-effects model.

The B_i's are possible future earthquake occurrence scenarios (e.g., a particular sequence of dates, locations, and magnitudes). For the small probabilities of engineering interest, it is normally adequate to replace the second factor above by the expected number of events in T years of each size originating from each unit volume of the earth's crust in the surrounding region.

The probabilities (or expectations) of the B_i's are the outputs of the stochastic earthquake recurrence model. In general, the probabilities or expectations related to the occurrences of future events should depend on the current "state," e.g., the times, locations, and sizes of the more recent events in the region (Cornell and Winterstein, 1986). These are examples of spatial and temporal dependence (see below).

Examples of descriptions of these hazard integration schemes were given by Cornell (1968), McGuire (1978b), der Kiureghian and Ang (1977), Savy and others (1981), Bernreuter and others (1985), Esteva (1976), and Cornell and Winterstein (1986). All but the latter two take advantage of the strong independence assumptions of the Poisson model (see below).

The assessment and analysis of the uncertainties in such probabilistic hazard studies has become routine in practice. Uncertainty, as defined here, reflects the degree of statistical and physical information upon which the probability (future frequency) estimates are based. In seismic hazard analysis, it has become popular to use "logic trees," i.e., discrete representations of alternative, uncertain parameter values and/or alternative model elements (e.g., different functional forms of ground-motion prediction equations or different tectonic models). See, for recent examples, Yankee Atomic Electric Company (1985), Bernreuter and others (1985), and Electric Power Research Institute (EPRI, 1985). This discrete tree-structure format has the advantage both of facilitating the treatment of conditional uncertainty assignments, (e.g., the mean rate of activity may depend on the tectonic model) and of encouraging as explicit a treatment of model uncertainty as is normally given parametric uncertainty. Here model uncertainty might include the considera- tion of one tectonic model that implies stationary seismicity and another, alternative model that favors evolutionary or even abrupt changes in seismicity over the next 10,000 years.

Any proper uncertainty methodology will mechanically propagate uncertainty in the model and on the parameters through the hazard analysis to produce uncertainty or confidence bands on the probability assessments.

Recurrence Models

Standard Poisson Exponential Model

Description. The standard assumption in most probabilistic analyses of seismic shaking (e.g., Cornell, 1968; Bernreuter and others, 1985; EPRI, 1985) is that earthquakes occur as a Poisson process (Parzen, 1962). A key property of the Poisson process is lack of memory; the probability distribution of the time to the next earthquake is independent of the time since the previous earthquake. This unique property manifests itself in two characteristics of the Poisson process: exponentially distributed inter-arrival times, with a coefficient of variation (COV) equal to 1 and constant hazard function. (The hazard function h(t) indicates the probability that an earthquake will occur in the near future given that the last earthquake occurred t years ago.)

In addition to the Poisson assumption, the assumption is routinely made that the magnitude and location of the next event are independent of the time since the previous earthquake, its magnitude, and its location.

Finally, it is generally assumed that magnitudes follow a doubly-truncated exponential distribution and that locations follow a piecewise-uniform distribution; each region of uniformity is called a seismic source and is usually associated with a geologic or tectonic feature or an area of high historic seismicity. The characteristic earthquake magnitude model studied by Youngs and Coppersmith (1985) does not have an exponential distribution of magnitude, but it is still a Poisson model.

This is the simplest probabilistic model of earthquake occurrence that can be formulated; it has the highest possible degree of probabilistic independence. In essence, the only parameters of this model are the expected number of earthquakes per year for each magnitude class and each seismic source.

Data Needs and Availability. The Poisson model requires as data a catalog of time, magnitude, and location of past earthquakes. Traditionally, most studies have used the historic record of seismicity. If the earlier period of non-instrumental reporting is included, this data base in the US spans at most less than 400 years. If only the later period of instrumental recording is included, the data base spans less than a century. The entire process of estimating parameters for a Poisson occurrence model (including analysis of dependent events, catalog incompleteness, common magnitude scale conversion, determination of spatial rates of occurrence, and estimation of magnitude distribution) is documented by Veneziano and Van Dyck (1985), who have recently developed the most rigorous, systematic approaches to these various problems.

In recent years, investigators have begun to combine the historic seismic records with paleoseismic information (see Chapter 4) on earthquakes that occurred in a more distant past (e.g., Schwartz and Coppersmith, 1984; Youngs and Coppersmith, 1985). Paleoseismic methods have been widely applied in the western US; application to the eastern US has met with more limited success.

Another critical parameter in these models is the maximum possible magnitude that a feature can generate. The typical historic record of earthquakes during a few hundred years is usually of limited use in evaluating maximum magnitude (McGuire, 1977b) because most maximum-magnitude events have mean inter-arrival times much longer than the historic record. Estimates based on fault dimensions (Slemmons, 1977; Wyss, 1979) have been widely used in the western US. More subjective methods have been used in the eastern US (EPRI, 1985).

Merits and Limitations. The assumptions of Poisson arrivals and full independence among magnitudes, locations, and inter-arrival times are physically unrealistic; they are not consistent with the widely accepted theories on accumulation and release of tectonic strains, which suggest a complex pattern of dependencies between occurrence-time, magnitude, and location of earthquakes.

Poisson models do not reproduce the observed pattern of smaller earthquakes that may occur before (foreshocks) and after (aftershocks) a large earthquake (Kagan and Knopoff, 1976; Kanamori, 1981). Studies have shown, however, that secondary shocks contribute only modestly to the seismic hazard, at least for facilities that do not undergo damage accumulation (Merz and Cornell, 1973; Veneziano and Van Dyck, 1985). Thus, inability of the Poisson models to predict secondary shocks is not a major drawback.

More significantly, recent work on historic and prehistoric patterns of occurrence of large earthquakes in selected seismic features indicates that the pattern of large earthquakes exhibits more regularity than the Poisson model would predict (e.g., Sykes and Quittmeyer, 1981; Sykes and Nishenko, 1984). This regularity manifests itself in a distribution of inter-arrival times with a COV smaller than unity and a hazard function that increases with time (the longer the time since the last large earthquake, the higher the probability of a large earthquake in the near future). The Poisson assumption works better on an aggregate of seismic sources than on an individual feature, because the sum of several independent non-Poisson processes approaches a Poisson process (Brillinger, 1982). Thus, even if the Poisson assumption is not realistic for a single feature, it may produce realistic hazard estimates for a site that is threatened by earthquakes from several features.

A recent study by Cornell and Winterstein (1986) suggests that these deviations from Poisson may not have a large effect on the hazard calculations even for nuclear plants threatened by a single feature, mostly because these plants have design lives of only some fifty years. The effects on hazard of longer-term deviations from Poisson have also been studied by McGuire (1979) and McGuire and Barnhard (1981), who used the Chinese earthquake catalog. They also concluded that the effect was small because of the short design life of typical facilities. The effect on hazard of deviations from Poisson has also been studied by Brillinger (1982). Deviations from Poisson behavior are likely to be more important for waste repositories than for nuclear plants for two main reasons: the very long design life and the potential for cumulative effects. This issue requires considerably more study.

A problem in estimating seismicity for the evaluation of seismic hazard to nuclear repositories, which is related to the very long design life of waste repositories and which is not limited to Poisson models, is the possibility of changes in current tectonic regimes. Even when good paleoseismic information is available, estimating steady state seismicity levels is not without difficulty. Estimating trends, let alone sudden changes (Bender, 1984), is clearly difficult and requires additional input from researchers in the earth sciences. There is some evidence that such changes occur very slowly. For instance, Zoback and Zoback (1980, 1981) note that directions of principal stresses and patterns of deformation in some regions vary on a time scale of tens of millions of years. One could allow for the possibility of such a change using discrete model alternatives (logic trees).

Models with Temporal Memory

Description. A number of magnitude-recurrence models that contain more memory than the Poisson model have been proposed. Some of these models try to incorporate certain dependencies suggested by a physical understanding of tectonic processes.

Renewal-process models (e.g., Esteva, 1976; Cornell and Winterstein, 1986) differ from the Poisson model in that the distribution of inter-arrival times is not necessarily exponential. Thus, one can choose an inter-arrival time distribution with the desired COV and with an increasing hazard function.

Dependence between inter-arrival time and magnitude is introduced in the so-called time-predictable and slip-predictable models. In time-predictable models (Shimazaki and Nakata, 1980; Anagnos and Kiremidjian, 1984), the distribution of the time to the next earthquake is dependent on the size of the previous earthquake: the larger the previous earthquake, the longer the wait to the next earthquake. In slip-predictable models (Shimazaki and Nakata, 1980; Kiremidjian and Anagnos, 1984), the distribution of earthquake magnitude depends on the time since the previous earthquake. A combined time-slip predictable model (with backward and forward memory) has been analyzed by Cornell and Winterstein (1986). The general semi-Markov model (Patwardhan and others, 1980) can also include all these possible dependencies.

A "characteristic-process" model, in which a feature produces two kinds of earthquakes, has been postulated by Cornell and Winterstein (1986). Large (characteristic) earthquakes follow a renewal-process model with a small COV of inter-arrival times, and smaller (background) earthquakes follow a Poisson-exponential model.

Data Needs and Availability. These recurrence models contain more parameters than the Poisson-process model and require more data. The simplest renewal-process model has one more parameter that must be estimated: the inter-arrival time, COV (Cornell and Winterstein, 1986). The time-predictable and slip-predictable models require at least one more parameter, to characterize dependence between inter-arrival times and magnitudes.

In addition to model parameters, the current state of the process should be estimated. This might be the date and size of last major event on the fault. The inter-arrival times of characteristic earthquakes may be very large, however, larger in fact than the period of observed seismicity. Thus, the time and magnitude of the previous earthquake may be unobserved. Such state descriptions can also be analyzed, however.

Merits and Limitations. These models introduce some physical realism, which is lacking in the Poisson-process model. They are still crude, ignoring, for example, spatial relationships among earthquakes (Singh and others, 1981). These models have not been tested in practice and the methods for parameter estimation and treatment of parameter/state uncertainty are not fully developed. A few studies have attempted to apply these models to practical hazard-analysis situations (Esteva, 1976; Savy and others, 1981; Cornell and Winterstein, 1986).

The effect of departures from Poisson on the seismic hazard at a nuclear repository--considering the long time-frame and the possibility of cumulative effects--have not been investigated. In principle, the magnitude of these effects depends on the extent and type of departure shown by the data and on the resulting uncertainty in parameters and states. The larger the uncertainty on parameters and states, the closer the marginal hazard (integrated over all uncertain variables) will be to the corresponding result for a Poisson model. Uncertainty in the hazard (as a result of uncertain parameters) may not be the same for the Poisson and non-Poisson models.

Models with Temporal and Spatial Dependence

Description. Some models attempt to predict the temporal and spatial dependence of seismicity. An example of this dependence is the highly enhanced likelihood of earthquakes occurring on seismic gaps (Singh and others, 1981).

A hybrid stochastic-mechanical model of earthquake occurrences in space and time was developed by Veneziano and Cornell (1974). A Markov model in space and time has been proposed by Kiremidjian and Anagnos (1980). See also Anagnos (1984).

Physical models that include stress accumulation, rupture initiation, and (static or dynamic) rupture propagation have been investigated by several authors (e.g., Burridge and Knopoff, 1967; Dietrich, 1972, 1979; Andrews, 1978; Stuart, 1985). Combined with a stochastic-process description of strength along the fault, these models have a potential for engineering applications.

Data Needs and Availability. Estimating parameters and current state for these models presents major difficulties, especially for the mechanical and hybrid models. As noted by Veneziano and Cornell (1974), the state variables (current state of stress on different fault segments) are many and can not be observed directly. As a result, the estimation problem is highly complicated, and the estimates obtained have low precisions.

Merits and Limitations. Models with temporal and spatial dependence have the potential for more realistic seismic-hazard estimates. Further understanding of the mechanics of faulting and direct measurements of stresses will increase the applicability these models. In application, these models might be used to improve the specification and estimation of parameters in simpler temporal-memory models.

These models are still research tools and have not yet reached the level of development needed for engineering applications. In particular, model uncertainty is still large, and parameters/state uncertainty will be large if past earthquakes are the only available data.

Ground Shaking

This subsection begins by describing the possible effects of ground shaking on the behavior of the repository. This is done to help define the kind of ground-shaking information that is needed. Next, it describes the quantities used by engineers and seismologists to characterize the intensity of earthquake shaking at a site. Finally, it describes the differences between earthquake shaking at depth and on the ground surface. In the subsections that follow, the different methods for the prediction of ground shaking are described, evaluated, and compared. State-of-the-art reviews on the prediction of earthquake shaking have been written by Swanger and others (1980, 1981), Hays (1980), Aki (1982), Boore (1983a), and Scholl and King (1985).

Earthquake-induced shaking may affect the performance of repositories during the period of waste loading and after closure. The mechanisms of damage during the loading period would be similar to those experienced in a deep mining operation: damage to above-ground facilities, damage to the vertical conveyance system, rock spalling, and collapse of tunnels. All these mechanisms may potentially lead to releases of radioactivity from waste temporarily stored above ground, in transit, or in permanent storage. The mechanisms of damage after backfilling and closure of the repository may compromise the integrity of one or more of the following containment barriers:

- the rock mass in the vicinity of the opening,
- the tunnel liner,
- the closure system (backfill and plugs), or
- the waste package.

Mechanical damage to the waste package would likely be caused by unsatisfactory performance of the backfill or the rock mass, not by the shaking itself.

A number of analytical studies and limited empirical evidence from earthquakes and explosions suggest that tunnels are less susceptible to shaking-induced damage than conventional, above-ground structures (Newmark, 1963; Dowding and Rozen, 1978; Dowding, 1979; Dowding and others, 1983; Hendron and Fernandez, 1983, Wu and others, 1983). The presence of backfill would further improve the strength of the tunnels and reduce the spatial extent of damage, as compared with empty tunnels. The magnitude of this effect depends on the mechanical properties of the backfill material.

Site ground shaking during an earthquake is most commonly characterized in terms of one or more of the following quantities: peak acceleration, peak velocity, and peak displacement. Another common measure, more directly related to the shaking of structures, is the spectral displacement SD(f,d), which is defined as the peak displacement of a linear mechanical oscillator of natural frequency f and damping (a measure of energy dissipation) equal to d percent of critical. A plot of SD(f,d) as a function of frequency f is called the response spectrum; approximate methods exist for constructing response spectra from peak acceleration, velocity, and displacement. Less common in practice, yet useful (at least on a conceptual basis), are the Fourier amplitude spectrum of ground acceleration and the duration of significant shaking (Trifunac and Brady, 1975; McGuire and Barnhard, 1979; Vanmarcke and

Lai, 1980). These quantities are discussed in detail in the earthquake engineering literature (e.g., Newmark and Rosenblueth, 1979; Clough and Penzien, 1975; Newmark and Hall, 1982). Peak acceleration is the most commonly used measure of shaking, but it has numerous drawbacks (Kennedy and others, 1984). For instance, two shaking episodes with the same peak acceleration--one from a large-magnitude, distant earthquake and the other from a moderate-magnitude, close-in earthquake--produce substantially different shaking in a typical structure. This is particularly true if the close-in earthquake occurs in the eastern US, where ground motions may contain a substantial fraction of their energy at high frequencies (>10 hertz); such energy does not affect the vibration of typical structures with low and moderate fundamental frequencies.

The amplitude, frequency content, and duration of shaking at a site on the surface is the combined effect of three factors: seismic source characteristics, propagation of seismic waves in the crust, and local effects due to soil and subsoil conditions. Most measurements of shaking are made at sites on the surface. Earthquake ground shaking in deep tunnels is different from that on the surface even at rock sites because the following site effects are absent: amplification caused by a free surface and filtering of high-frequency waves by weathered bedrock beneath the site.

The free-surface effect on the different wave types is well understood and documented (Anderson, 1976; Aki and Richards, 1980, Chapter 5). For a simplified model of the crust (i.e., a homogeneous half-space), theory predicts amplification at the surface by a factor of two for S_H waves and by a factor that depends on the angle of incidence (but remains approximately equal to two for a wide range of angles) for S_V waves. Empirical studies cited by Wight (1979) indicate that ground-motion amplitude at depth is typically 50% to 70% of that experienced at the surface, in agreement with theory. A recent review of downhole recordings by Chang and others (1986) indicates amplitudes at depth equal to about 20% of those experienced at soil sites on the surface; soil is probably responsible for the difference from the figure given by Wight.

Regarding the filtering of high-frequency ground motions by weathered rock, Hanks (1982) argued that the seismic source generates energy at higher frequencies, but the observed sharp cutoff at about 10 to 15 Hz (in California) is due to such filtering. In fact, measurements of ground motions in deep mines (McGarr and others, 1981) during small earthquakes at very small hypocentral distances indicates uniform frequency content up to frequencies of several hundred hertz. (Papageorgiou and Aki (1983a, 1983b) argued that the frequency cutoff is a source effect; furthermore, Aki (1985a) argued that the source cutoff frequency is higher for smaller earthquakes.) If Hanks's (1982) argument is correct, ground motions with more energy at high frequencies should be expected in deep tunnels during close-in earthquakes. For conventional structures, frequencies above 50 Hz are much higher than the structure's fundamental frequency and the structure does not respond to energy at these frequencies. For tunnels, on the other hand, the transverse fundamental frequency calculated from a diameter of 4 m is roughly 400 Hz

(McGarr and others, 1981) and the tunnel responds to (but does not amplify) energy at frequencies below 200 Hz. This high-frequency energy may or may not be damaging to the tunnel and lining depending on their rheological properties. For example, some materials, such as wood, are much more resistant to short-term loading than to long-term loading.

Direct Empirical Methods

Description. Empirical methods for the prediction of ground shaking date back to the 1960's and have been used extensively in probabilistic seismic-hazard analysis. These methods use (usually linear) regression analysis to fit an equation to a data base on the peak amplitude of ground motion, earthquake magnitude, and distance to the earthquake.

The functional form most commonly used in these regressions is

$$\ln Y = a_0 + a_1 M + a_2 \ln R + a_3 R + e \qquad (8\text{-}1)$$

in which Y is the peak amplitude of ground motion, M is the earthquake magnitude, R is the distance between the recording site and the earthquake, and e is a random error. Equations of this type are often called attenuation equations. The functional form of the above equation has some theoretical justification: the dependence of ln Y on M is based on the definition of earthquake magnitude (Richter, 1958), and the distance terms are based on the theoretical decay of body waves on homogeneous viscous media. Coefficient a_2 represents decay due to geometric spreading of energy, and coefficient a_3 represents energy dissipation (often called anelastic attenuation).

The above equation is written in logarithmic form in order to make it linear on the unknown coefficients a_0 through a_3. It has also been observed that the error term e has a distribution well represented by a normal (gaussian) distribution. Many variations on the above equation have been used. Some include a term for soil effects; others include magnitude-distance interaction terms (Campbell, 1981b); a few others have functional forms other than logarithmic (Bolt and Abrahamson, 1982; Brillinger and Priesler, 1984a, 1984b).

Y may be any of the measures of ground shaking discussed earlier, although peak acceleration is the most common. Root-mean-square (rms) acceleration was used by McCann (1980); response spectral ordinates were used by McGuire (1977a) and by Boore and Joyner (1982); Fourier spectral ordinates were used by McGuire (1978a), Trifunac and Brady (1976), and Cornell and others (1979). M is the earthquake magnitude, which is a measure of earthquake size; many magnitude scales exist (Nuttli and Herrmann, 1980). The most commonly used measure of distance, R, is the closest distance to the fault trace. As large earthquakes are usually associated with long ruptures (Slemmons, 1977; Bonilla, 1967; Joyner, 1984), the predicted isoseismals (i.e, lines of equal shaking) from large earthquakes are elongated rather than circular in shape.

Idriss (1978) summarized the early work on empirical prediction of ground motion. Among the more recent empirical studies on California data, the work of Joyner and Boore (1981), Campbell (1981b), and Boore and Joyner (1982) is in common use. These studies include data from the 1971 San Fernando earthquake and 1979 Imperial Valley earthquake. These two earthquakes produced more recordings than previous earthquakes. In order to prevent these two earthquakes from excessively influencing the regression analysis, Joyner and Boore (1981) and Boore and Joyner (1982) used a two-stage regression scheme, whereas Campbell (1981b) applied a weighting scheme. A more elegant, and statistically more efficient, treatment of this problem is given by Brillinger and Priesler (1984a, 1984b), who used a "random effects" model. A similar approach was used by Veneziano and Heidari (1986) in their analysis of ground shaking in eastern North America.

An important issue in empirical ground-motion prediction is whether, at small distances, the marginal increase in amplitude of shaking is smaller for large magnitudes than for small magnitudes (a phenomenon known as saturation). Campbell (1981b) predicted saturation, but Joyner and Boore (1981) showed that the data can not distinguish between models with and without saturation.

Prior distributions on one or more of the parameters a_0 through a_3 may be introduced when the data are limited; simple regressions may lead to unacceptable estimates or very large standard errors on some of the parameters (Veneziano and Heidari, 1986).

Data Needs and Availability. A large number of processed earthquake recordings are needed in order to obtain a large number of points in the space of (ln Y, M, ln R, and R). Recordings from California earthquakes before 1976 have been processed by the Earthquake Engineering Laboratory of the California Insitute of Technology (Hudson, 1976; see also McGuire and Barnhard, 1977, for magnitude and distance information). Recordings from more recent earthquakes have been processed by the California Division of Mines and Geology and by the US Geological Survey.

The California data set can be considered adequate for the prediction of shaking at distances larger than 20 km for magnitudes smaller than 6. For smaller distances and larger magnitudes, data are scarce, and predictions are very much dependent on the assumed functional form (Askins, 1980).

For other regions of the US, where the seismic activity and density of strong-motion seismographs are substantially lower, the available strong-motion data are much more limited.

Toro and McGuire (1986) compiled data on shaking from North American earthquakes east of the 105th meridian. The largest earthquake in this data set has m_{bLg} 5.6 (m_{bLg} is a magnitude scale commonly used for earthquakes in the eastern and central US; see Nuttli and Herrmann, 1980); data for distances smaller than 100 km are available only for m_{bLg} smaller than 5.

Data from recordings of smaller earthquakes and/or large distances are available for Eastern North America (Atkinson, 1985; Gupta and others, 1985). In spite of their very low amplitudes, these data are often used in the absence of better data.

The aforementioned data come from instruments located on Earth's surface. Recordings from underground instruments are limited and not sufficient for the application of empirical analysis. A small number of underground recordings were described by Chang and others (1986).

Merits and Limitations. Direct empirical methods are adequate if the data set contains sufficient data over the range of magnitudes and distances that dominate hazard at the site. Insufficient data cause two problems: predictions may be highly sensitive to the assumed functional form of the regression model (high model uncertainty), and the parameter estimates may have very large standard errors (high statistical uncertainty). In the worst (but not unrealistic) case, some parameter estimates may not be statistically significant or may take values that violate physical principles.

For all regions except California, the available ground-level earthquake recordings are insufficient for the fitting of empirical relations to be used in the prediction of ground shaking for the magnitude and distance ranges of engineering interest. (Relationships derived from California data are presumably applicable to the entire Pacific Northwest, as long as differences in focal depth are properly considered.)

The situation is much worse for underground recordings. Calculation of "pseudo"-underground recordings by removing the surface effects from ground-level recordings is possible (Joyner and others, 1981; Chang and others, 1986) but requires knowledge of the local soil profile and introduces additional uncertainties.

In summary, given the limitations in the available data, empirical methods, while perhaps adequate for conventional surface facilities, are not well suited for the prediction of ground shaking in underground repositories.

Indirect Empirical Methods

Description. As mentioned earlier, the number of available instrumental strong-motion recordings is small for most areas outside California. Non-instrumental information, from reports of the perceived intensity of shaking and the observed extent of structural damage, is often more abundant. (This is the case in the eastern and central US.) Non-instrumental information is measured on the Modified Mercalli Intensity scale (MMI; see Richter, 1958).

Attenuation relations for intensity have been obtained by many authors (e.g., Bernreuter and others, 1985; Veneziano, 1985) in terms of magnitude and distance, of epicentral intensity and distance, and of distance (for specific individual earthquakes). Several authors have substituted these attenuation relations into empirically obtained relationships between instrumental measures of shaking as a function of intensity and (possibly) other variables such as magnitude and distance. The net result is an attenuation function of the standard type; namely, amplitude of shaking as a function of magnitude and distance.

McGuire (1984) and Bernreuter and others (1985; and references therein) illustrated the use of these methods. Cornell and others (1979) applied these methods to California data and concluded that most substitution procedures were biased; i.e., they did not yield the same coefficients as the direct regression of magnitude and distance on amplitude of ground motion. Veneziano and Heidari (1986) have developed an unbiased procedure and applied it to the estimation of peak accelerations and response spectral ordinates for the eastern and central US. These authors have developed statistical diagnostics that indicate whether the regressions being combined are compatible and procedures to treat incompatibilities.

Data Needs and Availability. Sources of data on Modified Mercalli Intensity from earthquakes in the eastern US and Canada are listed by Bernreuter and others (1985) and Eckert and Atkinson (1985). Intensity data are generally more abundant than instrumental data, but their quality is lower. In order to avoid biases in using intensity data, the analyst should be aware of how intensity is assigned to a given locale and how intensity information is compiled (see Veneziano and Heidari, 1986).

Abundant data from California, where both instrumental and MMI information are available, can be used to fit relationships for amplitude of shaking as a function of intensity, (and possibly) magnitude, and distance (see Bernreuter and others, 1985, for examples of such relationships).

Merits and Limitations. For regions where there are abundant MMI data but there are few or no instrumental data, unbiased formulations of the indirect method (as developed by Veneziano and Heidari, 1986) are superior to direct methods because they incorporate additional information. Like direct empirical methods, these methods are hampered by the virtual absence of instrumental recordings at depth, even in California.

Semi-Empirical Methods

Description. In trying to overcome the dearth of instrumental ground-motion data in regions outside California, investigators have devised a number of procedures that combine data with predictions from theory.

Nuttli (1979) fixed the coefficients a_1 through a_3 in Eq. (8-1) using theoretical arguments. Coefficient a_0 was calibrated using data from the San Fernando, California, earthquake.

Campbell (1981a, 1982) used a variant of Eq. 8-1, with a_3 fixed to a value consistent with anelastic attenuation in California. He fit that equation to the California data set of Campbell (1981b). Then, he modified the resulting coefficients to convert from the magnitude scales used in his regression to m_b and to reflect anelastic attenuation in the central US.

Nuttli (1983a) fixed the values of coefficients a_1 through a_3 based on theory (the value of a_1 is based on the scaling of source spectra proposed by Nuttli, 1983b) and calibrated a_0 to data from the central US.

Bernreuter and others (1985) described a similar method.

Merits and Limitations. Semiempirical methods are at least partially successful in overcoming the limitations of limited data in areas other than California. These methods are not without their problems. The magnitude coefficients (i.e., a_1 in Eq. 8-1) used by Nuttli (1979, 1983a) are based on the spectral-scaling model of Nuttli (1983b; see also Street and others, 1975). (A spectral-scaling model determines how the Fourier amplitude spectrum of acceleration near the source varies with earthquake size.) This spectral model has been recently criticized by Boore and Atkinson (1986). Also, the eastern US data used by Nuttli (1983a) come mostly from recordings on soft soils, which may have amplified ground shaking.

One possible problem with Campbell's (1981a, 1982) relationship is the magnitude conversion, which is effectively performed by substituting one regression into another. As documented by Cornell and others (1979) and Veneziano and Heidari (1986), substitution of one regression into another may lead to biased results. (The biases should be smaller, however, for magnitude conversions, where correlation is stronger, than for MMI-to-ground-shaking conversions.)

As with direct and indirect empirical methods, removal of the local site effects--from the input data or from the model's result--in order to obtain peak motions at depth is a difficult problem that introduces additional uncertainty in the results.

Stochastic Methods

Stochastic methods use a probabilistic representation of the energy radiated by the seismic source or of the slip on the fault. They use simple concepts of wave-propagation theory to model the effect of propagation path and free-surface amplification. Stochastic methods may be divided into two broad categories: those that start from a more abstract representation of the seismic source and those that model the kinematics or dynamics of slip on the fault. Aki (1985b, 1985c) reviewed methods in these two categories and their relationship to deterministic methods.

Most methods in the first category use the source spectral representation of Brune (1971, 1972), which relates the amplitude and shape of the Fourier spectrum of acceleration to two parameters: seismic moment (a measure of earthquake size; see Aki and Richards, 1980, and Hanks and Kanamori, 1979) and stress drop on the fault. (Some authors prefer to consider stress drop an empirical, rather than physical, parameter.) For given seismic moment, stress drop, and distance, these methods yield the power spectral density and duration of ground acceleration. Peak accelerations, velocities, spectral displacements, and other measures of ground motion are then calculated using random-vibration theory (Crandall and Mark, 1963; see also Boore, 1983b). In essence, these methods are not too different from the semi-empirical scaling methods of Nuttli (1979, 1983a); they differ only in their assumptions about source scaling and in their mathematical rigor.

Stochastic methods satisfactorily predict ground motion in California (Hanks and McGuire, 1981; McGuire and Hanks, 1980; Boore, 1983b; McGuire and others, 1984). In these applications, the stress drop has been assumed constant and equal to 100 bars. The same value of stress drop has been used to predict ground motions in eastern Canada (Atkinson, 1984) and eastern North America (Boore and Atkinson, 1986; Toro and McGuire, 1986). Results show reasonable, albeit not perfect, agreement with the limited data available.

Herrmann (1985) extended these methods to the prediction of eastern US ground motions at distances of several hundred kilometers by introducing, in an approximate manner, the dispersive nature of Lg waves, which dominate shaking at those distances. This result is important because it allows comparison of model predictions with the more distant recordings that constitute most of the instrumental data in those regions (Eckert and Atkinson, 1985; Gupta and others, 1985; Toro and McGuire, 1986).

Methods in the second category date back to the work of Aki (1966) and Haskell (1966). More recently, Papageorgiou and Aki (1983a, 1983b, 1985) have proposed a model in which the earthquake rupture is represented as an aggregate of circular cracks of equal diameter, which represent coseismic slip. As the rupture front sweeps the fault plane, a stress drop takes place in each crack. The diameter of the cracks is one of the model parameters. Savy and others (1981) and Savy (1980) have proposed a model in which slip along the fault and propagation of the rupture front are random functions. Other models have been proposed by Boatwright (1982), Gusev (1983), and Faccioli (1985). These models have been used mostly in an inverse mode; i.e., given a well recorded and documented earthquake, which parameters will best reproduce the these observations?

Data Needs and Availability. Stochastic methods require data for calibrating parameters and verifying assumptions. Recordings from seismograph instruments (which measure shaking from more distant events) are often useful for these purposes (e.g., Sommerville and others, 1985), thus increasing the availability of data. Other diverse sources of data that can be used to calibrate and verify the assumptions of stochastic models include geological observations and theoretical studies in seismology.

Merits and Limitations. Stochastic methods are less dependent on scarce strong-motion data than empirical methods, which makes them more attractive for areas like the eastern and central US. Stated differently, if the data force us to extrapolate from distant and low-magnitude recordings, it is better to perform the extrapolation with the model that has the strongest theoretical justification.

Some assumptions in the first category of methods are controversial. For the eastern US, there is debate on whether stress drops are constant or increase with seismic moment (see Nuttli, 1983b; Sommerville and others, 1985; Boore and Atkinson, 1986).

Methods in the second category have more parameters, which are sometimes hypothesized to vary from earthquake to earthquake and (presumably) from region to region. These parameters must be specified, either as one deterministic value or as an uncertain (fixed but unknown) or random quantity that must be treated accordingly in the analysis.

In principle, these methods are not sensitive to the lack of data on ground motion at depth, i.e., all that is needed to predict ground motion at depth is to remove the factor of two that accounts for free-surface amplification and the low-pass filter that accounts for the effect of weathered rock near the surface. In practice, this is not entirely the case. For instance, Boore (1986) revised the stress-drop estimate for California on the argument that surface recordings on rock were amplified because the rocks typical of California rock sites are less rigid than Earth's crust. Also, there are the two conflicting views on the origin of the high-frequency cutoff observed on ground-level recordings (see introduction to this Section).

Deterministic Methods

Description. Deterministic methods generate synthetic "seismograms" from a (usually kinematic) representation of slip at the source and detailed modeling of wave propagation through detailed models of the crust. These methods date to the work of Aki (1968) and Haskell (1969), in which a smooth temporal and spatial distribution of slip along the fault plane is assumed. More recently, investigators have refined the models by adding the effect of free-surface and layered-crustal models (e.g., Archuleta and Frazier, 1978; Heaton and Helmberger, 1978; Archuleta, 1985). Most of these methods use non-uniform spatial distributions of slip; usually, the distribution of slip is modified until agreement is obtained with the observed suite of seismograms being modelled.

In order to properly model the frequencies of engineering interest, observed records from smaller events are summed to yield the ground motion from a larger earthquake (Kanamori, 1979; Hadley and Helmberger, 1980; Hartzell, 1985). Munguia and Brune (1985) add a random component to the smooth slip distribution in order to represent the observed ground motions.

Data Needs and Availability. Deterministic models require detailed knowledge of crustal properties. The popular layered-earth models require knowledge of the depth, density, wave velocity, and damping for each layer.

A priori specification of the distribution of fault slip in space and time is difficult.

Merits and Limitations. In their present state of development, simulation methods have a limited range of applicability for predicting high-frequency ground shaking of engineering interest.

Earthquake Faulting

Earthquake faulting near an underground repository may seriously affect repository performance. Faulting may create a path of reduced or increased flow resistance for contaminated ground water. In addition, if the fault rupture intersects the repository itself, the integrity of the engineered barriers (i.e., tunnel liner, backfill and plugs, and waste package) will be compromised. The effects of faulting may also compound the effects of failure--due to shaking--of the liner, the backfill, or the waste package.

We will concern ourselves with evaluating the probability that the repository, or a volume of rock that includes the repository, will be intersected by seismic faulting. Evaluating the effect of faulting or fault movement on the ground-water flow regime is beyond the scope of this volume.

Current estimates of the probability of faulting near a repository vary widely. For instance, Wight (1979) suggested that the probability be taken as unity, whereas Trask (1982) suggested a very low probability.

Two classes of models are available for evaluating probabilities of faulting. First, the same models used to estimate probabilities of ground shaking can be modified to predict probabilities of faulting at the site. We will call these magnitude-occurrence models. Second, one can can develop a probabilistic characterization of fault generation, without using earthquake magnitude as an intermediate variable. We will call these faulting-occurrence models.

<u>Magnitude-Occurrence Models of Faulting</u>

<u>Description.</u> In a magnitude-occurrence model of faulting, as in models for the probabilistic characterization of shaking, earthquake occurrences are characterized as a marked point process in space and time; magnitude is used to characterize earthquake size. Instead of an attenuation function, an influence function characterizes the extent of faulting. The influence function takes values of zero (no faulting) or one (faulting), may be defined in three dimensions (i.e., it includes rupture depth), and may be anisotropic (i.e., the rupture is likely to follow some preferred directions of faulting). The extent of the influence function depends on magnitude, but it has a random component.

A model of this type has been used by Kiremidjian (1984) to investigate the probability of damage of aqueducts by earthquake faulting. This model uses influence functions in two dimensions and assumes that ruptures will follow the orientation of existing faults (highly anisotropic influence functions). As shown in the above reference, all that is needed is the characterization of fault size (and possibly the extent of fault slip) as a function of magnitude. Magnitude-occurrence models have also been used by Otsuka (1964) and Logan and Berbano (1977).

Kiremidjian's (1984) method can easily be modified to consider the three-dimensional geometry of rupture and repository and for regions where no active faults have been identified and earthquakes are hypothesized to occur on broad seismic sources. The data needed for a geometric characterization of rupture are discussed next.

Data Needs and Availability. In addition to the data needed to characterize the spatial and temporal distribution of earthquakes, a magnitude-occurrence model of faulting requires a probabilistic description of rupture geometry (length, width, depth, dip, and complexity) as a function of magnitude.

There is a large body of observational evidence on rupture length, width, and depth as functions of magnitude, collected in California and other regions where there is high seismic activity and earthquakes rupture the surface.

Rupture length as a function of magnitude has been investigated by Bonilla (1973, 1979, 1982), Bonilla and Buchanan (1970), Bonilla and others (1984), and Slemmons (1977, 1982). Observational information on rupture width may be obtained from aftershock maps, but no such compilation of widths as a function of magnitude is known to the author. Physical considerations provide some guidance as to width (Sibson, 1977, 1982). Information on rupture width may also be obtained from the relationship for rupture area as a function of magnitude proposed by Wyss (1979). Focal depth was studied by Sibson (1982) and by Chen and Molnar (1983). Some of these regressions predict magnitude as a function of rupture dimensions and should not be used in reverse. Instead of inverting these equations, the original data should be used to develop regressions for rupture dimensions as functions of magnitude.

Fault complexity, subsidiary faulting, and fault-zone thickness affect the probabilistic calculations (in the sense that the rupture may have a non-infinitesimal thickness). Subsidiary faulting will also affect the calculations of ground-water flow given that faulting near the repository has occurred. These aspects of faulting have been studied by Bonilla (1979), Sharp (1979), Wallace (1979), and Speed (1979). There is no agreement on whether fault complexity on the surface is representative of fault complexity at depth. According to Wallace (1979), fault-zone thickness is related to cumulative fault displacement. To the author's knowledge, no quantitative (empirical or physical) studies have been performed on predicting fault complexity as a function of magnitude and surface geology; a notable exception is a compilaton by Wight (1979) of fault-zone thickness from a number of large earthquakes.

Most of the observational data mentioned heretofore come from earthquakes that occurred on existing faults (Bonilla, 1979). It is of interest to predict rupture geometry when the earthquake ruptures intact rock or healed faults. Rupture dimensions (inferred from aftershock or geodetic studies) from earthquakes in the eastern US and similar regions can provide a limited data base for the development of empirical relationships for fault dimensions. Physical considerations, such as relationships between seismic moment, stress drop, and source dimensions (Brune, 1971, 1972) are also useful in this context.

Merits and Limitations. The critical requirement of the magnitude-occurrence model is the probabilistic characterization of rupture geometry as a function of magnitude. For regions like California (and, perhaps, everywhere west of the Rocky Mountains), observational data and understanding of the tectonic processes are sufficient for the development of such a probabilistic model; a systematic statistical re-evaluation of the empirical data is probably in order. For other regions, data are scarce and one must rely heavily on seismological models of faulting. In consequence, model uncertainty is likely to be higher.

The probabilistic characterization of earthquake occurrences used in these models is the same one used in probabilistic models of ground shaking. Thus, the experience gained in seismic shaking studies during the last 15 years can be transferred to this problem. For the eastern and central US, methodological developments for treating uncertainty and estimating recurrence parameters from historic seismicity and tectonic regime are available (EPRI, 1985).

Faulting-Occurrence Models

Description. Faulting-occurrence models directly attempt to characterize the occurrence of faulting as a random process in space and time. A probabilistic model of this type has been proposed by Cranwell and Donath (1980), who modeled the generation of faults as a Poisson process in time and space. They suggested a mechanical model where the rates of faulting are calculated from the distributions of fault orientation and strength and from the tectonic stress regime. Some aspects of the above model resemble the magnitude-occurrence models.

Brooke (1978) has studied the spatial distribution of faults in selected regions.

Trask (1982) suggested that the neotectonic history of broad regions be used to estimate the rates of recurrence of fault movements of faults in these regions. He proposed to use slip rates determined from paleoseismic studies; slip rates can be transformed into recurrence intervals using theoretical (Anderson, 1979) or empirical (Slemmons, 1977) approaches. Trask (1982) summarized information on state of stress and slip rates in seven regions and estimated the yearly rate of faulting events. He also summarized seven previous site-specific studies.

It has been noted by several authors (e.g., Bonilla, 1982; Zoback and Thompson, 1978) that most earthquake rupturing occurs in preexisting faults or other zones of weakness. Studies that focus on existing faults should allow for the possibility of undetected faults (Wight, 1979; Logan and Berbano, 1977; Bertozzi and others, 1977; Cranwell and Donath, 1980). The model by Cranwell and Donath (1980) can be used to estimate probabilities of non-detection.

A few other models have been proposed in the literature; they are specific to particular sites, but they illustrate alternative approaches.

The studies by the Engineering Decision Analysis Company (1979) and Benjamin and Associates (1980) estimated the probability of faulting beneath a building that is located between two faults. The basic assumptions of the former model are (1) faulting events constitute a Poisson process (Parzen, 1962); (2) given that one slip event occurs, there is a probability q that the slip occurs between the existing fault instead of occuring in the two faults that currently exist, independently of where previous slips occurred; (3) given one occurrence of slip between the faults that currently exist, the location of that fault follows a certain probability distribution. A Bayesian analysis (Benjamin and Cornell, 1971) was used to estimate the main parameters (annual rate of slip events and q) using as data the information on historic offsets at the fault during a period of 100,000 to 200,000 years and the evidence of no faulting between the two known faults during that period.

Howland and others (1983) used a mechanical (finite element) model of the local geologic structure to investigate the probability that the offset underneath a building exceeds a certain value. The critical parameters of the mechanical model were assumed to be random variables. The force and displacement boundary conditions driving the mechanical model were not described. In principle, these boundary conditions may be either deterministic (e.g., constant slip rates) or probabilistic.

<u>Data Needs and Availability.</u> Fault-occurrence models require information on the spatial and temporal occurrence of faulting events and on the distribution of fault size and orientation.

Information on the spatial pattern and density of faulting is obtained from geological reconaissance studies, remote imagery, aerial photography, geophysical measurements, and microseismicity. Methods based on the surface expression of faulting are difficult to apply in the eastern US.

Information on the yearly number of events on a fault is obtained from slip rates. Slip rates are determined using paleoseismic methods (see Ch. 4), which provide approximate dates and displacements of past slip events. In the western US, slip rates have been estimated for a large number of faults (Trask, 1982; Wallace, 1981). In the eastern US, there are relatively few faults on which Quaternary movement can be demonstrated and for which slip rates can be estimated (Trask, 1982; EPRI, 1985). There is also more uncertainty in how to convert slip rates to recurrence rates in the eastern US. The regional approach proposed by Trask (1982) partially alleviates the problems created by the dearth of data. If all faults in a region are assumed to have identical behavior, more conclusions can be drawn from slip rates determined on a few faults.

<u>Merits and Limitations.</u> Conceptually, fault-occurrence methods are attractive because they deal directly with the phenomenon of interest; namely faulting. Most magnitude scales measure the moderate-to-high frequency content of earthquake-induced motion, whereas the extent of faulting is better measured by the zero-frequency component of motion. As a consequence, regressions between rupture size and magnitude show large scatter (e.g., Bonilla, 1982). Thus, direct collection of data in terms of rupture size (as opposed to magnitude) should lead to higher precision in the probabilistic estimates of faulting.

The limited success of paleoseismic methods in the eastern US restricts the applicability there of fault-recurrence methods. Also, there is considerably less experience on the application of fault-occurrence methods than on magnitude-occurrence methods for the prediction of shaking.

Discussion of Currently Available Approaches

The methods and subelements of seismic hazard analysis are adequate for application to the shorter-term (10- to 100-year), surface operations of a repository; they are in current use for similar applications. Improving the regional data upon which parameter estimates are based is always desirable, especially with respect to (non-Californian) ground motion predictions, but with any given data level, hazard estimates should always be accompanied by quantitative uncertainty statements.

There is virtually no experience base for the unique problem of long-term (10,000-year), subsurface repository assessment with respect to ground motion and faulting. The general framework of seismic hazard analysis, including uncertainty assessment, is, however, flexible enough to incorporate this problem. The successful application will require the development, exploration, and likelihood assessment of a suite of alternative recurrence models. (The simple Poisson model may not remain attractive, except perhaps in areas of higher seismicity (Cornell and Winterstein, 1986).) This modeling effort should parallel tectonic assessments (Chapter 4) including reviews of seismicity and tectonic changes during windows of similar durations in similar regions to assist the estimation of the probabilities of significant changes from the current regime in the region of interest.

The estimation of ground motion at depth could be improved substantially in the next 10 years by the (not inexpensive) expedient of upgrading the down-hole strong-motion instrumentation program in the US and elsewhere. Resolution of the high-frequency differences (surface vs. at-depth) would be particularly valuable. The current uncertainty in the difference may, however, be acceptably small in view of uncertainties elsewhere and the likely lack of sensitivity of the underground facility to the ground motion levels in question.

Predicting the degree of faulting at a site given a seismic event is probably more critical to the facility, but improvements in the current data base cannot be accelerated. It will therefore be important to capture well the uncertainty in the probabilistic predictions.

References

Aki, K., 1966, "Scaling Law of Seismic Spectrum," Jour. Geophys. Research, vol. 72, p. 1217-1231.

Aki, K., 1968, "Seismic Displacements Near a Fault," Jour. Geophys. Research, vol. 73, p. 5359-5376.

Aki, K., 1982, "Strong Motion Prediction Using Mathematical Modeling Techniques," Bull. Seismol. Soc. Amer., vol. 72, p. S1-S13.

Aki, K., 1985a, "Origin of f_{max}", Submitted to Jour. Geophys. Research.

Aki, K., 1985b, "An Overview and Issues: Review of Simulation Procedures," in R. E. Scholl and J. L. King, eds., Strong Ground Motion Simulation and Earthquake Engineering Applications, Publication No. 85-02, Earthquake Engineering Research Institute, Berkeley, CA, p. 11-1--11-9.

Aki, K., 1985c, "Technical Evaluation: Source Effects," in R. E. Scholl and J. L. King, eds., Strong Ground Motion Simulation and Earthquake Engineering Applications, Publication No. 85-02, Earthquake Engineering Research Institute, Berkeley, CA, p. 33-1--33-7.

Aki, K., and P. G. Richards, 1980, Quantitative Seismology, Freeman, San Francisco, CA.

Anagnos, T., 1984, A Stochastic Earthquake Recurrence Model with Temporal and Spatial Dependence, Ph.D. Thesis, Department of Civil Engineering, Stanford University, Stanford, CA.

Anagnos, T., and A. S. Kiremidjian, 1984, "Stochastic Time-Predictable Model for Earthquake Occurrences," Bull. Seismol. Soc. Amer., vol. 74, p. 2593-2611.

Anderson, J. G., 1976, "Motions Near a Shallow Rupturing Fault: Evaluation of the Effect due to the Free Surface," Jour. Geophys. Research, vol. 16, p. 575-593.

Anderson, J. G., 1979, "Estimating Seismicity from Geologic Structure for Seismic Risk Studies," Bull. Seismol. Soc. Amer., vol. 69, p. 135-158.

Andrews, D. J., 1978, "Coupling of Energy Between Tectonic Processes and Earthquakes," Jour. Geophys. Research, vol. 83, p. 2259-2264.

Archuleta, R. J., 1985, "Simulating the Near Source Ground Motion of the 1979 Imperial Valley Earthquake," in R. E. Scholl and J. L. King, eds., Strong Ground Motion Simulation and Earthquake Engineering Applications, Publication No. 85-02, Earthquake Engineering Research Institute, Berkeley, CA.

Archuleta, R. J., and G. A. Frazier, 1978, "Three-Dimensional Numerical Simulation of Dynamic Faulting in a Half-Space," Bull. Seismol. Soc. Amer., vol. 68, p. 541-572.

Askins, R. C., 1980, Advanced Statistical Techniques for Seismic Hazard Attenuation Law Estimation, M.S. Thesis, Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, MA.

Atkinson, G. M., 1984, "Attenuation of Strong Ground Motion in Canada from a Random Vibrations Approach," Bull. Seismol. Soc. Amer., vol. 74, p. 2629-2653.

Atkinson, G. M., 1985, Ground Motions from Moderate Earthquakes Recorded by the Eastern Canadian Telemetered Network, Earth Physics Branch Open File Report No. 85-5, Seismological Service of Canada.

Bender, B., 1984, "A Two-State Poisson Model for Seismic Hazard Estimation," Bull. Seismol. Soc. Amer., vol. 74, p. 1463-1468.

Benjamin, Jack R., and Associates, 1980, Additional Probability Analysis of Surface Rupture Offset Beneath Reactor Buildings, General Electric Test Reactor, JBA-111-013-01, prepared for General Electric Company, San Jose, CA, variously paginated.

Benjamin, J. R., and C. A. Cornell, 1971, Probability, Statistics, and Decisions for Civil Engineers, McGraw Hill, New York, 864 pp.

Bernreuter, D. L., J. B. Savy, R. W. Mensing, J. C. Chen, and B. C. Davis, 1985, Seismic Hazard Characterization of the Eastern United States, UCID-20421, Vols. 1 and 2, Lawrence Livermore National Laboratory, Livermore, CA.

Bertozzi, G., M. D'Alessandro, F. Girardi, and M. Vanossi, 1977, "Evaluation de la Surete du Stockage de Dechets Readioactifs en Formations Geologiques: une application Preliminaire de la 'Fault Tree Analysis' a des Formations Salines," Risk Analysis and Geologic Modelling in Relations to the Disposal of Radioactive Wastes into Geologic Formations, Proceedings of a Workshop Organized Jointly by the Nuclear Energy Agency, OECD, and the Commision of the European Communities.

Boatwright, J., 1982, "A Dynamic Model of Far-Field Acceleration," Bull. Seismol. Soc. Amer., vol. 72, p. 1049-1068.

Bolt, B. A., and N. A. Abrahamson, 1982, "New Attenuation Relations for Peak and Expected Accelerations of Strong Ground Motion," Bull. Seismol. Soc. Amer., vol. 72, p. 2307-2321.

Bonilla, M. G., 1967, Historic Surface Faulting in Continental United States and Adjacent Parts of Mexico, Open-file Report, US Geological Survey, 36 pp.

Bonilla, M. G., 1973, "Surface Faulting and Related Effects," in R. L. Weigel, ed., Earthquake Engineering, Prentice Hall, Englewood Cliffs, NJ, p. 47-74.

Bonilla, M. G., 1979, "Historic Surface Faulting--Map Patterns, Relations to Subsurface Faulting, and Relation to Preexisting Faults," Proc. Conf. VIII, Analysis of Actual Fault Zones in Bedrock, Open-file Report 79-1239, US Geological Survey, p. 36-65.

Bonilla, M. G., 1982, Evaluation of Potential Surface Faulting and Other Tectonic Deformation, Open-file Report 82-732, US Geological Survey.

Bonilla, M. G., and J. M. Buchanan, 1970, Interim Report on Worldwide Historic Surface Faulting, Open-file Report, US Geological Survey.

Bonilla, M. G., R. K. Mark, and J. J. Lienkaemper, 1984, Statistical Relations between Earthquake Magnitude, Surface Rupture Length and Surface Fault Displacement, Open-file Report 84-256, US Geological Survey.

Boore, D. M., 1983a, "Strong-Motion Seismology," US National Report to International Union of Geodesy and Geophysics: Contributions in Seismology, Amer. Geophys. Union, p. 1308-1318.

Boore, D. M., 1983b, "Stochastic Simulation of High-Frequency Ground Motions Based on Seismological Models of the Radiated Spectra," Bull. Seismol. Soc. Amer., vol. 73, p. 1865-1984.

Boore, D. M., 1986, "Short-Period P- and S-Wave Radiation from Large Earthquakes: Implications for Spectral Scaling Relations," Bull. Seismol. Soc. Amer., vol. 76, p. 43-64.

Boore, D. M., and G. M. Atkinson, 1986, "Prediction of Ground Motion and Spectral Response Parameters in Eastern North America," submitted to the Bull. Seismol. Soc. Amer., March.

Boore, D. M., and W. B. Joyner, 1982, "The Empirical Prediction of Ground Motion," Bull. Seismol. Soc. Amer., vol. 72, p. S269-S286.

Brillinger, D. R., 1982, "Some Bounds for Seismic Risk," Bull. Seismol. Soc. Amer., vol. 72, p. 1403-1410.

Brillinger, D. R., and H. K. Preisler, 1984a, "An Exploratory Analysis of the Joyner-Boore Attenuation Data," Bull. Seismol. Soc. Amer., vol. 74, p. 1441-1450.

Brillinger, D. R., and H. K. Preisler, 1984b, "Further Analysis of the Joyner-Boore Attenuation Data," Bull. Seismol. Soc. Amer., vol. 75, p. 611-614.

Brooke, J., 1978, "Geomathematical Investigation of Fault Populations at Selected Locations," 19th US Rock Mechanics Symposium, Lake Tahoe, CA.

Brune, J. N., 1971, "Tectonic Stress and the Spectra of Seismic Shear waves from Earthquakes," Jour. Geophys. Research, vol. 75, p. 4997-5002.

Brune, J. N., 1972, "Correction," Jour. Geophys. Research, vol. 76, p. 5002.

Burridge, R., and L. Knopoff, 1967, "Models and Theoretical Seismicity," Bull. Seismol. Soc. Amer., vol. 57, p. 341-371.

Campbell, K. W., 1981a, "A Ground Motion Model for the Central United States Based on Near Source Acceleration Data," Earthquakes and Earthquake Engineering: Eastern U.S., Ann Arbor Science Publ., Ann Arbor, MI.

Campbell, K. W., 1981b, "Near Source Attenuation of Peak Horizontal Acceleration," Bull. Seismol. Soc. Amer., vol. 71, p. 2039-2070.

Campbell, K. W., 1982, "A Preliminary Methodology for the Regional Zonation of Peak Acceleration," Proc. Third Internat. Conf. Earthquake Microzonation, Seattle, WA.

Chang, C.-Y, M. S. Power, I. M. Idriss, P. G. Sommerville, W. Silva, and P. C. Chen, 1986, Engineering Characterization of Ground Motion, Task II: Observational Data on Spatial Variations of Earthquake Ground Motions, NUREG/CR-3805, Vol. 3, US Nuclear Regulatory Commission.

Chen, W., and W. P. Molnar, 1983, "Focal Depths of Intracontinental and Intraplate Earthquakes and Its Implications for the Thermal and Mechanical Properties of the Lithosphere," Jour. Geophys. Research, vol. 88, p. 4183-4214.

Clough, R. W., and J. Penzien, 1975, Dynamics of Structures, McGraw Hill, New York.

Cornell, C. A., 1968, "Engineering Seismic Risk Analysis," Bull. Seismol. Soc. Amer., vol. 58, p. 1583-1606.

Cornell, C. A., and S. R. Winterstein, 1986, Applicability of the Poisson Earthquake Occurrence Model, Eastern U.S. Seismic Hazard Assessment Project, Electric Power Research Institute, Palo Alto, CA.

Cornell, C. A., H. Banon, and A. F. Shakal, 1979, "Seismic Motion and Response Prediction Alternatives," Earthquake Engineering and Structural Dynamics, vol. 7, p. 295-315.

Crandall, S. H., and W. D. Mark, 1963, Random Vibration of Mechanical Systems, Academic Press, New York.

Cranwell, R. M., and F. A. Donath, 1980, "An Application of Geometric Probability to the Existence of Faults in Anisotropic Media," in C. J. M. Northrup, ed., Scientific Bases for Nuclear Waste Management Vol. 2, Plenum Press, New York, p. 787-794.

der Kiureghian, A., and A. H.-S. Ang, 1977, "A Fault-Rupture Model for Seismic Risk Analysis, Bull. Seismol. Soc. Amer., vol. 67, p. 1173-1194.

Dietrich, J. H., 1972, "Time-Dependent Friction as a Possible Mechanism of Aftershocks," Jour. Geophys. Research, vol. 77, p. 3771-3781.

Dietrich, J. H., 1979, "Modeling of Rock Friction, 2, Simulation of Pre-Seismic Slip," Jour. Geophys. Research, vol. 84, p. 2169-2175.

Dowding, C. H., 1979, "Earthquake Stability of Rock Tunnels," Tunnels and Tunneling, vol. 11, p. 15-20.

Dowding, C. H., and A. Rozen, 1978, "Damage to Rock Tunnels from Earthquake Shaking," Jour. Geotechnical Div., Amer. Soc. Civil Engineers, vol. 104, p. 175-192.

Dowding, C. H., C. Ho, and T. Belytschko, 1983, "Earthquake Response of Caverns in Jointed Rock," in T. R. Howard, ed., Seismic Design of Embankments and Caverns, Amer. Soc. Civil Engineers, New York.

Eckert, A., and G. M. Atkinson, 1985, "Ground Motion Data in Eastern North America," Seismic Hazard Methodology for Nuclear Facilities in the Eastern United States, Vol. 3, EPRI Research Project P101-29, Electric Power Research Institute, Palo Alto, CA.

Electric Power Research Institute, 1985, Seismic Hazard Methodology for Nuclear Facilities in the Eastern United States, Vol. 1, EPRI Research Project P101-29, Electric Power Research Institute, Palo Alto, CA.

Engineering Decision Analysis Company, 1979, Probability Analysis of Surface Rupture Offset Beneath Reactor Building: General Electric Test Reactor, EDAC-117-217.13, Engineering Decision Analysis Company, Palo Alto, CA.

Esteva, L., 1976, "Seismicity," in C. Lomnitz and E. Rosenblueth, eds., Seismic Risk and Engineering Decisions, Elsevier, Amsterdam, p. 179-224.

Faccioli, E., 1985, "A Study of Strong Motions from Italy and Yugoslavia in Terms of Gross Source Properties," 5th Maurice Ewing Symposium on Earthquake Source Mechanics, Amer. Geophys. Union, Harriman, NY.

Gupta, I. N., K. L. McLaughlin, and R. A. Wagner, 1985, Attenuation of Ground Motion in the Eastern United States, Electric Power Research Institute, Palo Alto, CA.

Gusev, A. A., 1983, "Descriptive Statistical Model of Earthquake Source Radiation and its Application to an Estimation of Short-Period Strong Motion," Geoph. Jour., Royal Astronom. Soc., vol. 74, p. 787-808.

Hadley, D. M., and D. V. Helmberger, 1980, "Simulation of Strong Ground Motions," Bull. Seismol. Soc. Amer., vol. 70, p. 617-630.

Hanks, T. C., 1982, "f_{max}", Bull. Seismol. Soc. Amer., vol. 72, p. 1867-1879.

Hanks, T. C., and H. Kanamori, 1979, "A Moment Magnitude Scale," Jour. Geophys. Research, vol. 84, p. 2348-2350.

Hanks, T. C., and R. K. McGuire, 1981, "The Character of High-Frequency Strong Ground Motion," Bull. Seismol. Soc. Amer., vol. 71, p. 2071-2095.

Hartzell, S., 1985, "The Use of Small Earthquakes as Green's Functions," in R. E. Scholl and J. L. King, eds., Strong Ground Motion Simulation and Earthquake Engineering Applications, Publication No. 85-02, Earthquake Engineering Research Institute, Berkeley, CA.

Haskell, N. A., 1966, "Total Energy and Energy Spectral Density of Elastic Wave Radiation from Propagating Faults: Part II. A Statistical Source Model," Bull. Seismol. Soc. Amer., vol. 56, p. 125-140.

Haskell, N. A., 1969, "Elastic Displacements in the Near Field of a Propagating Fault," Bull. Seismol. Soc. Amer., vol. 59, p. 865-908.

Hays, W. W., 1980, Procedures for Estimating Earthquake Ground Motions, Prof. Paper 1114, US Geological Survey.

Heaton, T. H., and D. V. Helmberger, 1978, "Predictability of Strong Ground Motion in the Imperial Valley: Modeling the M 4.9 November 4, 1976, Brawley Earthquake," Bull. Seismol. Soc. Amer., vol. 68, p. 31-48.

Hendron, A., Jr., and G. Fernandez, 1983, "Dynamic and Static Considerations for Underground Chambers," in T. R. Howard, ed., Seismic Design of Embankments and Caverns, Amer. Soc. Civil Engineers, New York.

Herrmann, R. B., 1985, "An Extension of Random Vibration Theory Estimates of Strong Ground Motion to Large Distances," Bull. Seismol. Soc. Amer., vol. 75, p. 1447-1453.

Howland, J. D., W. H. Roth, R. K. McGuire, and J. Sweet, 1983, "Probabilistic Analysis of a Geomechanical Prediction of Ground Surface Rupture," Presented at Seismic Risk and Heavy Industrial Facilities Conference, San Francisco, CA, May.

Hudson, D. E., 1976, Strong Motion Earthquake Accelerograms--Index Volume, Report No. EERL 76-02, Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena, CA.

Idriss, I. M., 1978, "Characteristics of Earthquake Ground Motions," Presented at Specialty Conference on Earthquake Engineering and Soil Dynamics, Amer. Soc. Civil Engineers, Pasadena, CA.

Joyner, W. B., 1984, "A Scaling Law for the Spectra of Large Earthquakes," Bull. Seismol. Soc. Amer., vol. 74.

Joyner, W. B., and D. M. Boore, 1981, "Peak Horizontal Acceleration and Velocity from Strong Motion Records Including Records from the 1979 Imperial Valley, California, Earthquake," Bull. Seismol. Soc. Amer., vol. 71, p. 2011-2038.

Joyner, W. B., R. E. Warrick, and T. E. Fumal, 1981, "The Effect of Quaternary Alluvium in Strong Ground Motion in the Coyote Lake, California, Earthquake of 1979," Bull. Seismol. Soc. Amer., vol. 71, p. 1349-1981.

Kagan, Y. Y., and L. Knopoff, 1976, "Statistical Search for Non-Random Features of the Seismicity of Strong Earthquakes," Phys. Earth Planet. Inter., vol. 12, p. 291-318.

Kanamori, H., 1979, "A Semi-Empirical Approach to Prediction of Long-Period Ground Motions for Great Earthquakes," Bull. Seismol. Soc. Amer., vol. 69, p. 1645-1670.

Kanamori, H., 1981, "The Nature of Seismic Patterns Before Large Earthquakes," in D. W. Simpson and P. G. Richards, eds., Earthquake Prediction, an International Review, Amer. Geophys. Union, Washington, DC.

Kennedy, R. D., S. A. Short, K. L. Merz, F. J. Tokarz, I. M. Idriss, M. S. Power, and K. Sadigh, 1984, Engineering Characterization of Ground Motion, Task I: Effects of Characteristics of Free Field Motions on Structural Response, NUREG/CR-3805, US Nuclear Regulatory Commission.

Kiremidjian, A. S., 1984, "Reliability of Structures Subjected to Differential Fault Slip," Earthquake Engineering and Structural Dynamics, vol. 12, p. 603-618.

Kiremidjian, A. S., and T. Anagnos, 1980, "A Homogeneous Alternating Markov Model for Earthquake Occurrences," Proc. 7th Conf. Earthquake Engineering, Istanbul, Turkey.

Kiremidjian, A. S., and T. Anagnos, 1984, "Stochastic Slip-Predictable Model for Earthquake Occurrences," Bull. Seismol. Soc. Amer., vol. 74, p. 739-755.

Logan, S. E., and M. C. Berbano, 1977, "Geologic Modelling in Risk Assessment Methodology for Radioactive Waste Management," Risk Analysis and Geologic Modelling in Relations to the Disposal of Radioactive Wastes into Geologic Formations, Proceedings of a Workshop Organized Jointly by the Nuclear Energy Agency, OECD, and the Commission of the European Communities.

McCann, M. W., 1980, RMS Acceleration and Duration of Strong Ground Motion, Rept. 46, J. A. Blume Earthquake Engineering Center, Stanford University, Stanford, CA.

McGarr, A., R. W. E. Green, and S. M. Spottiswoode, 1981, "Strong Ground Motion of Mine Tremors, Some Implications for Near Source Ground Motion Parameters," Bull. Seismol. Soc. Amer., vol. 71, p. 295-319.

McGuire, R. K., 1977a, "Seismic Design Spectra and Mapping Procedures using Hazard Analysis Based Directly on Oscillator Response," Internat. Jour. Earth. Eng. and Struct. Dyn., vol. 5, p. 211-234.

McGuire, R. K., 1977b, "Effect of Uncertainty in Seismicity on Seismic Hazard in the East Coast of the United States," Bull. Seismol. Soc. Amer., vol. 67, p. 827-848.

McGuire, R. K., 1978a, "A Simple Model for Estimating Fourier Amplitude Spectra of Horizontal Ground Acceleration," Bull. Seismol. Soc. Amer., vol. 68, p. 803-822.

McGuire, R. K., 1978b, FRISK--A Computer Program for Seismic Risk Analysis Using Faults as Earthquake Sources, Open-file Report 78-1007, US Geological Survey.

McGuire, R. K., 1979, "Adequacy of Simple Probability Models for Calculating Felt-Shaking Hazard, Using the Chinese Earthquake Catalog," Bull. Seismol. Soc. Amer., vol. 69, p. 877-892.

McGuire, R. K., 1984, "Ground Motion Estimation in Regions with Few Data," Proc. Eight World Conf. Earthquake Engineering, San Francisco, CA, Vol. II, p. 327-334.

McGuire, R. K., and J. A. Barnhard, 1977, "Magnitude, Distance, and Intensity Data for C.I.T. Strong Motion Records," US Geological Survey, Jour. Research, vol. 5.

McGuire, R. K., and T. P. Barnhard, 1979, Four Definitions of Strong-Motion Duration: Their Predictability and Utility for Seismic Hazard Analysis, Open-file Report 79-1515, US Geological Survey.

McGuire, R. K., and T. P. Barnhard, 1981, "Effects of Temporal Variations in Seismicity on Seismic Hazard," Bull. Seismol. Soc. Amer., vol. 71, p. 321-334.

McGuire, R. K., and T. C. Hanks, 1980, "RMS Accelerations and Spectral Amplitudes of Strong Ground Motion during the San Fernando, California, Earthquake," Bull. Seismol. Soc. Amer., vol. 70, p. 1907-1920.

McGuire, R. K., A. M. Becker, and N. C. Donovan, 1984, "Spectral Estimates of Seismic Shear Waves," Bull. Seismol. Soc. Amer., vol. 74, p. 1427-1440.

Merz, H. A., and C. A. Cornell, 1973, Aftershocks in Engineering Risk Analysis, Research Report R73-25, Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, MA.

Munguia, L., and J. N. Brune, 1985, "Simulation of Strong Ground Motion for Earthquakes in the Mexicali-Imperial Valley," in R. E. Scholl and J. L. King, eds., Strong Ground Motion Simulation and Earthquake Engineering Applications, Publication No. 85-02, Earthquake Engineering Research Institute, Berkeley, CA.

Newmark, N. M., 1963, "Design of Structures for Dynamic Loads Including the Effects of Vibration on Ground Shock," Symp. Scientific Problems of Protective Construction, Swiss Federal Institute of Technology, Zurich.

Newmark, N. M., and W. J. Hall, 1982, Earthquake Spectra and Design, Earthquake Engineering Research Institute, Berkeley, CA.

Newmark, N. M., and E. Rosenblueth, 1979, Fundamentals of Earthquake Engineering, Prentice-Hall, Englewood Cliffs, NJ.

Nuttli, O. W., 1979, State of the Art for Assessing Earthquake Hazards in the United States, Report 16, The Relation of Sustained Maximum Ground Acceleration and Velocity to Earthquake Intensity and Magnitude, Misc. Paper S-73-1, US Army Engineers Waterways Experimental Station, Vicksburg, MS.

Nuttli, O. W., 1983a, "Letter of January 24, 1983," in D. L. Bernreuter, J. B. Savy, R. W. Mensing, J. C. Chen, and B. C. Davis, 1985, Seismic Hazard Characterization of the Eastern United States, UCID-20421, Vols. 1 and 2, Lawrence Livermore National Laboratory, Livermore, CA.

Nuttli, O. W., 1983b, "Average Seismic Source Parameter Relations for Midplate Earthquakes," Bull. Seismol. Soc. Amer., vol. 73, p. 519-535.

Nuttli, O. W., and R. B. Herrmann, 1980, "Earthquake Magnitude Scales," Jour. Geotech. Engineering Div., Amer. Soc. Civil Engineers, p. 783-786.

Otsuka, M., 1964, "Earthquake Magnitude and Surface Fault Formation," Jour. Phys. Earth, vol. 12, p. 19-24.

Papageorgiou, A. S., and K. Aki, 1983a, "A Specific Barrier Model for the Quantitative Description of Inhomogeneous Faulting and the Prediction of Strong Ground Motion. I. Description of the Model," Bull. Seismol. Soc. Amer., vol. 73, p. 693-722.

Papageorgiou, A. S., and K. Aki, 1983b, "A Specific Barrier Model for the Quantitative Description of Inhomogeneous Faulting and the Prediction of Strong Ground Motion. II. Application of the Model," Bull. Seismol. Soc. Amer., vol. 73, p. 953-978.

Papageorgiou, A. S., and K. Aki, 1985, "Scaling Law of Farfield Spectra Based on Observed Parameters of the Specific Barrier Model," Submitted to Jour. Geophys. Research.

Parzen, E., 1962, Stochastic Processes, Holden Day, San Francisco, CA.

Patwardhan, A. S., R. B. Kulkarni, and D. Tocher, 1980, "A Semi-Markov Model for Characterizing Recurrence of Great Earthquakes," Bull. Seismol. Soc. Amer., vol. 70, p. 323-347.

Richter, C. F., 1958, Elementary Seismology, W. H. Freeman and Co., San Francisco, CA.

Savy, J. B., 1980, A Geophysical Model of Strong Motion for Large Ensemble Generation, Research Report R81-6, Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, MA.

Savy, J. B., H. C. Shah, and D. B. Boore, 1981, "Nonstationary Risk Model with Geophysical Input," Jour. Structural Div., Amer. Soc. Civil Engineers, vol. 106, p. 145-164.

Scholl, R. E., and J. L. King, eds., 1985, Strong Ground Motion Simulation and Earthquake Engineering Applications, Publication No. 85-02, Earthquake Engineering Research Institute, Berkeley, CA.

Schwartz, D., and K. J. Coppersmith, 1984, "Fault Behavior and Characteristic Earthquakes: Examples from the Wasatch and San Andreas Fault Zones," Jour. Geophys. Research, vol. 89, p. 5681-5698.

Sharp, R. V., 1979, "Implications of Surficial Strike-Slip Fault Patterns for Simplification and Widening with Depth," Proc. Conf. VIII, Analysis of Actual Fault Zones in Bedrock, Open-file Report 79-1239, US Geological Survey, p. 66-78.

Shimazaki, K., and T. Nakata, 1980, "Time-Predictable Occurrence for Large Earthquakes," Geophys. Research Let., vol. 7, p. 279-282.

Sibson, R. H., 1977, "Fault Rocks and Fault Mechanisms," Jour. Geol. Soc. London, vol. 133, p. 741-767.

Sibson, R. H., 1982, "Fault Zone Models, Heat Flow, and the Depth Distribution of Earthquakes in the Continental Crust of the United States," Bull. Seismol. Soc. Amer., vol. 72, p. 151-163.

Singh, S. K., L. Astiz, and J. Havskov, 1981, "Seismic Gaps and Recurrence Periods of Large Earthquakes along the Mexican Subduction Zone: A Re-examination," Bull. Seismol. Soc. Amer., vol. 71, p. 827-843.

Slemmons, D. B., 1977, State-of-the-Art for Assessing Earthquake Hazards in the United States, Report 6, Faults and Earthquake Magnitude, Miscellaneous Paper S-73-1, US Army Engineers Waterways Experimental Station, Vicksburg, MS.

Slemmons, D. B., 1982, "Determination of Design Earthquake Magnitude for Microzonation," Proc. Third Internat. Conf. Microzonation, Seattle, WA.

Sommerville, P., J. McLaren, R. Burger, V. LeFevre, and D. Helmberger, 1985, Source Scaling Relations of Eastern North American Earthquakes, Electric Power Research Institute, Palo Alto, CA.

Speed, R., 1979, "Extension Faulting in the Great Basin: Kinematics and Possible Changes with Depth," in R. C. Speed and R. V. Sharp, eds., Proc. Conf. VIII, Analysis of Actual Fault Zones in Bedrock, Open-file Report 79-1239, US Geological Survey, p. 36-65.

Street, R. L., R. B. Herrmann, and O. W. Nuttli, 1975, "Spectral Characteristics of the Lg Wave Generated by Central United States Earthquakes," Geophys. Jour., Royal Astronom. Soc., vol. 41, p. 51-63.

Stuart, W. D., 1985, "Instability Model for Recurring Large and Great Earthquake in Southern California," Pure Appl. Geophys., vol. 122, p. 793-811.

Swanger, H. S., S. M. Day, J. R. Murphy, and R. Guzman, 1980, State-of-the-Art Study Concerning Near Field Earthquake Ground Motion, NUREG/CR-1978, US Nuclear Regulatory Commission.

Swanger, H. S., J. R. Murphy, T. J. Bennett, and R. Guzman, 1981, State-of-the-Art Study Concerning Near Field Earthquake Ground Motion, NUREG/CR-1940, US Nuclear Regulatory Commission.

Sykes, L. R., and S. P. Nishenko, 1984, "Probabilities of Occurrence of Large Plate Rupturing Earthquakes for the San Andreas, San Jacinto, and Imperial Faults, California, 1983-2003," Jour. Geophys. Research, vol. 89, p. 5905-5927.

Sykes, L. R., and Quittmeyer, 1981, "Repeat Times of Great Earthquakes Along Simple Plate Boundaries," Earthquake Prediction, Maurice Ewing Series, vol. 4, Amer. Geophys. Union, p. 217-247.

Toro, G. R., and R. K. McGuire, 1986, "Random-Vibration Model of Ground Motions in the Eastern United States," Methods for Earthquake Ground-Motion Prediction for the Eastern United States, Electric Power Research Institute, Project RP2556-16, Palo Alto, CA.

Trask, N. J., 1982, Performance Assessment for Radioactive Waste Repositories: the Rate of Movement of Faults, Open-file Report 82-972, US Geological Survey.

Trifunac, M. D., and A. G. Brady, 1975, "A Study in the Duration of Strong Earthquake Ground Motion," Bull. Seismol. Soc. Amer., vol. 65, p. 581-626.

Trifunac, M. D., and A. G. Brady, 1976, "Preliminary Empirical Model for Scaling Fourier Amplitude Spectra of Strong Ground Acceleration in Terms of Magnitude, Source-to-Station Distance, and Recording Site Conditions," Bull. Seismol. Soc. Amer., vol. 66, p. 1343-1374.

Vanmarcke, E. H., and S. S. P. Lai, 1980, "Strong Motion Duration and RMS Amplitude of Earthquake Records," Bull. Seismol. Soc. Amer., vol. 70, p. 1293-1307.

Veneziano, D., 1985, "Statistical Estimation of Ground Motion Using MM Intensities," in Electric Power Research Institute, 1985, Seismic Hazard Methodology for Nuclear Facilities in the Eastern United States, Vol. 3, EPRI Research Project P101-29, Electric Power Research Institute, Palo Alto, CA.

Veneziano, D., and C. A. Cornell, 1974, Earthquake Models with Spatial and Temporal Memory for Engineering Seismic Risk Analysis, Research Report R74-78, Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, MA.

Veneziano, D., and M. Heidari, 1986, "Statistical Analysis of Attenuation in the Eastern United States," Methods for Earthquake Ground-Motion Prediction for the Eastern United States, EPRI Project RP2556-16, Electric Power Research Institute, Palo Alto, CA.

Veneziano, D., and J. M. Van Dyck, 1985, Seismic Hazard Methodology for Nuclear Facilities in the Eastern United States, Vol. 2: Appendix A, EPRI Research Project P101-29, Electric Power Research Institute, Palo Alto, CA.

Wallace, R. E., 1979, "Characteristics of Faults and Shear Zones as Seen in Mines at Depths as Much as 2.5 km Below the Surface," Proc. Conf. VIII, Analysis of Actual Fault Zones in Bedrock, Open-file Report 79-1239, US Geological Survey, p. 36-65.

Wallace, R. E., 1981, "Profiles and Ages of Young Scarps, North-Central Nevada," Bull. Geol. Soc. Amer., vol. 88, p. 1267-1281.

Wight, L. H., 1979, "Analysis of the Seismic Hazard to an Underground Waste Repository," in B. L. Scott, G. L. Benson, R. A. Craig, and M. A. Harwell, eds., Assessment of Effectiveness of Geologic Isolation Systems: A Summary of FY-1978 Consultant Input for Scenario Methodology Development, PNL-2851, Pacific Northwest Laboratories, Richland, WA, p. III-1--III-21.

Wu, C. L., S. W. Chen, and R. D. Wise, 1983, "Seismic Evaluation of Underground Facilities for Nuclear Waste Storage," Waste Management '83, Univ. of Arizona.

Wyss, Max, 1979, "Estimation of Maximum Expectable Magnitude of Earthquakes from Fault Dimensions," Geology, vol. 7, p. 336-340.

Yankee Atomic Electric Co., 1985, Seismic Source Method of Seismic Hazard Analysis and EQZONE Computer Code Manual, EPRI NP-4349-CCM, Electric Power Research Institute, Palo Alto, CA.

Youngs, J. J., and K. J. Coppersmith, 1985, "Implications of Fault Slip Rates and Earthquake Recurrence Models to Probabilistic Seismic Hazard Estimates," Bull. Seismol. Soc. Amer., vol. 75, p. 939-964.

Zoback, M. D., and G. A. Thompson, 1978, "Basin and Range Rifting in Northern Nevada: Clues from a midMiocene Rift and its Subsequent Offsets," Geology, vol. 6, p. 111-116.

Zoback, M. D., and M. L. Zoback, 1981, "State of Stress and Intraplate Earthquakes in the United States," Science, vol. 213, p. 96-104.

Zoback, M. L., and M. D. Zoback, 1980, "State of Stress in the Conterminous United States," Jour. Geophys. Research, vol. 85, p. 6113-6156.

Chapter 6

VOLCANOLOGY*

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Abstract

Methods of assessing the probability of volcanic disruption of a nuclear-waste repository differ widely, both in rationale and in reliability, depending on the geologic setting of the site. If its tectonic regime is well understood, a very stable region, such as the eastern United States, can be considered a very unlikely site for volcanic activity, but numerical calculations of a probability for an igneous event at a given site in such a region are less realistic than the considered opinion of experts who have examined its geologic setting. Quantitative estimates of probabilities are possible only in regions where Cenozoic volcanism has occurred within the same structural province as the proposed site and where detailed geological and geophysical studies have established patterns for the structural and magmatic evolution of the region. If rates and directions of these trends are known, they can be projected into the future, and if structural controls, spacing, and effective radii of potential events have been determined, one can calculate the probability of disruption of a site of any given size, shape, and depth.

Because volcanism tends to be strongly episodic, events cannot be taken as random, and because the nature and magnitude of eruptions are governed by factors such as the previous history of the system and the length of time between eruptions, events cannot be assumed to be independent of one another. It is necessary, therefore, to have enough data on the nature and age of previous activity to define patterns of frequency and trends of distribution in space and time. Provided these limitations are taken into account, the methods used to estimate volcanic hazards near recently active volcanic centers can be adapted to analyses of broader regions with infrequent prehistoric activity.

Introduction

This chapter reviews the methods of estimating the probabilities of an igneous event affecting a nuclear-waste repository in different geologic settings and assesses the limitations placed on the validity of these methods by the inherent nature of volcanic phenomena. The primary basis for any

*This chapter reviews and evaluates techniques for assigning probabilities to future igneous events. This review and evaluation does not imply that the NRC has endorsed the use of the techniques discussed.

estimate of volcanic hazards that could affect a nuclear-waste repository is the geological context of the site and the scale on which one attempts to forecast probabilities. Igneous processes can be considered on three scales: broad continent-wide regimes, regional settings of a single geologic province, and specific igneous centers. Each of these has its own characteristic features and must be evaluated according to different criteria. As a general rule, as the scale of investigation is restricted to smaller regions and shorter time periods, the data needed to assess future activity are better defined, and the validity of probability estimates tends to improve. The special problems associated with each scale of igneous activity will be outlined before considering the basis of probabilistic calculations that can be made for specific sites.

This chapter also includes a brief description of the limited work describing possible interactions between volcanic processes and a waste repository. Reports dealing with short-term predictions for recently active volcanoes have not been reviewed in this chapter unless they provide information on techniques that could bear on methods of calculating long-term probabilities of volcanic activity.

Geological Background

Broad Continent-Wide Regimes

The potential for igneous events in broad tectonic regimes is governed by global plate motion and large-scale crust-mantle relations. On this scale, methods of calculating probabilities depend almost entirely on interpretations of theoretical concepts, many of which are difficult to test by rigorous standards. The validity of these concepts must be evaluated from a fragmentary geologic record, and in many instances, this involves judgments with a large element of subjectivity. Data are drawn from geophysical observations on a continental scale and from a geologic record extending back millions of years. Two approaches can be used.

Tectonic Analyses of Structural Evolution. The first approach focuses on the distribution of volcanism in the North American plate for periods extending back into the Cenozoic for 15 or 20 million years. The data it draws on consist mainly of inferred plate motions, ages of volcanic episodes, compositional variations of magmas, and relations of activity to identifiable structural features on a continental scale. It seeks to establish patterns in the distribution of igneous centers that can be related to plate motions and intra-plate stress orientations. The approach is empirical in that it uses the past record of activity and extrapolates trends on the assumption of no major changes in the tectonic regime on a continental or global scale.

For example, the temporal and spatial distribution of volcanism along the western margin of the North American continent has been explained in terms of the interaction of the North American Plate with the East Pacific Rise. As the continent has overrun the spreading axis, subduction has ceased along the coast of North America, and after a delay of a few million years, the andesitic volcanism that dominated the region for several hundred million years has been progressively extinguished. This decline of activity has proceeded southward and northward at a nearly linear rate from the time of the initial intersection of the ridge with the American plate on the coast of California. Today it has reduced the zone of andesitic volcanoes to the Cascade Range and the Mexican Volcanic Belt. The region between the southern extremity of the Cascade Range in northern California and the mouth of the Gulf of California is essentially devoid of this type of volcanism.

Dating the rate of extinction of volcanism in a setting of this kind indicates that activity may continue for as long as 10 million years after the end of subduction, but most of the decline takes place in the first 2 or 3 million years. Thus, one could conclude that a region such as central California would be free of volcanism if at least 10 million years had passed since subduction ended and that volcanism would not resume unless there were another major change in the tectonic regime.

Analyses of Stress Distribution in Continental Plates. A second approach has been applied to intraplate regions where volcanism is related to large-scale deformation and tectonic stress patterns. Smith and Luedke (1984) studied the temporal and spatial distribution of igneous activity in the continental US and provided a basic source of information on potential volcanism on a regional scale. They examined the distribution of volcanism for the past 16 million years and found activity in the western states to be related to linear fault systems reflecting the orientation of stresses in the North American plate. As in the first approach, structural patterns identified in the field have been dated to measure rates of propagation. The trends in time and space obtained in this way can be projected into the future, and so long as the stress patterns remain the same, the location of future activity can be predicted. Smith and Luedke emphasized that the data are imprecise and that more study is needed.

Many studies of volcanism in different types of tectonic regimes have demonstrated that igneous activity seldom if ever reaches near-surface levels in regions undergoing strong compressive stresses (Williams and McBirney, 1979). Regions of intense folding and thrust faulting, such as parts of the Rocky Mountains, can therefore be ruled out as potential sites for most types of volcanism.

Potential Value for Probability Estimates. Most geologists would agree that both these methods are sound and are based on widely accepted tectonic interpretations. Although no quantitative estimates of probabilities have been attempted, the methods have been used to classify large regions of the continent as tectonically active or stable (Scott, 1978; Smith and Luedke, 1984; Tilling and Bailey, 1984). The entire eastern half of the continent, for example, could be assigned a very low probability of igneous activity, because it conforms to the criteria provided by this type of analysis.

The possibility of volcanism cannot be ruled out entirely, however. Most intraplate volcanoes in stable continental regions are thought to be related to persistent thermal anomalies or "hotspots" in the underlying mantle. These are readily identifiable as regional features and will be considered in the following section. Other eruptions come from isolated eruptive centers that seem to break out at random. Volcanoes of this latter type have appeared very infrequently in intraplate regions, such as Kansas, Missouri, and Kentucky, that are otherwise quite stable (Williams and McBirney, 1979). Most are small and so rare that if the probabilities of such events were calculated, they would be in a class with large meteoritic impacts. The effect of such events on a repository could be important, however, because even though the eruptions may be small, they tend to be highly explosive. Lacking historic examples, we have no way of knowing how well such an eruption could be forecast by geophysical means. It is thought that the rate of rise of such magmas is very rapid, and it is unlikely that premonitory phenomena would provide more than a few hours, or at most a few days, advance warning.

Global Distribution of Volcanism in Geologic Time. In the past few years, increasing evidence has indicated that volcanism is not randomly distributed in geologic time but tends to be concentrated in episodes that appear to be in phase on a global scale. Kennett and others (1977) distinguished periods of brief but intense activity at intervals of roughly 5 million years since early Miocene time. No clear relation has been identified between these episodes and tectonic events. At our present state of knowledge, it is impossible to account for the strong concentrations of volcanic activity in relatively short time intervals. At the present time, we appear to be passing through such a period of unusually intense volcanism. Kennett and Thunell (1975) analyzed the distribution of ash layers in marine sediments to demonstrate the strongly episodic nature of the most recent volcanism in the Circum-Pacific region. They stressed the sudden increase of activity in the past 2 million years and suggested a possible causal relationship to Pleistocene climatic changes. Judging from the duration of previous Cenozoic episodes, which has been of the order of one or two million years, the current episode may be approaching an end. Johnpeer and others (1981) also addressed the problem of estimating rates of eruptive activity in provinces where volcanism has been episodic and showed how this factor can affect probability estimates.

Any attempt to estimate rates of prehistoric volcanism must take this episodic distribution into account. Extrapolation of data on eruptive events that are compiled for a period falling between two such episodes would grossly underestimate future rates, for example.

Regional Settings of a Single Geologic Province

The potential for igneous events on a regional scale must be assessed in terms of the record of prior activity and the thermal and stress regimes in specific regions. Investigations required to assess probabilities at this scale would focus on a region within the effective radius of any igneous event that would have an impact on the specific site under investigation, but the geographic limits of the area to be examined will differ according to the type of activity being considered. Most studies have concluded that the most serious possible event on this scale would be a large-scale fissure eruption capable of blanketing thousands of square kilometers with flood lavas or pyroclastic flows (Bailey and others, 1983; Simkin and others, 1981).

Data will come from regional geological and geophysical studies designed to identify potential centers and the types of activity that could be associated with them. Studies of this type seek to identify either of two types of conditions, intraplate "hotspots" or dilational zones of faulting of the kind known to have been associated with volcanism in the past. The particular setting need not, however, have a history of past activity: potential volcanism may consist either of renewed eruptions from an established system or initial outbreaks from new vents.

An example of the "hotspot" setting would be the Yellowstone region, which, although it has no record of historic volcanism, has produced great sheets of rhyolitic ignimbrites covering tens of thousands of square kilometers in Wyoming, Utah, and Idaho. These outpourings have come in three distinct cycles, about 2.0, 1.3, and 0.6 million years ago. The probability of a future eruption on this time scale might be estimated in two ways. First, one can date previous events and find the average interval of repose between large-scale eruptions. These are normally on the scale of thousands to millions of years, but the regularity of spacing differs widely from one place to another. Second, no body of magma of this size could be mobilized without being preceded by conspicuous geophysical phenomena. At Yellowstone, uplift of the central part of the caldera complex during the last decade has been interpreted as the effect of a large mass of siliceous magma. A similar condition has been identified in Long Valley, California. No attempt has yet been made to estimate the probabilities of such premonitory phenomena leading to an igneous event, because we have no historic examples and therefore no records of their associated geophysical phenomena.

Nevertheless, it is possible to derive quantitative estimates of the time scale of previous activity and project these forward in time and space. For example, the San Francisco volcanic center in central Arizona has been shown to be migrating in a northeasterly direction at a rate of about 25 km/10^6 yr. It is a simple matter to predict the general area and time in which the next outbreak is likely to appear. Other examples of migrating centers of volcanism are found in central California and Oregon (Scott, 1978; Smith and Luedke, 1984; Tilling and Bailey, 1984) and the Snake River Plain of Idaho (Niccum and others, 1980).

The effective radius of large siliceous eruptions from centers related to these hotspots may extend for hundreds or even thousands of kilometers, if the activity produces large pyroclastic flows. The area affected by such an eruption would be so large compared to the dimensions of the vent complex that the exact location of the outbreak would be less important than the timing of the eruptive cycles. A clear relation has been demonstrated (Figure 6-1) between the length of the period of repose of these large eruptive centers and the magnitudes of ensuing explosive eruptions. The longer the interval between eruptions, the stronger the discharge tends to be (Simkin and others, 1981; Simkin and Siebert, 1982, 1984). The strongest explosive eruptions are most likely to come from old volcanic centers that have been inactive for periods of thousands or tens of thousands of years. The consequences of this relationship will be considered when discussing attempts to arrive at probabilistic estimates for such eruptions, but it should be emphasized here that

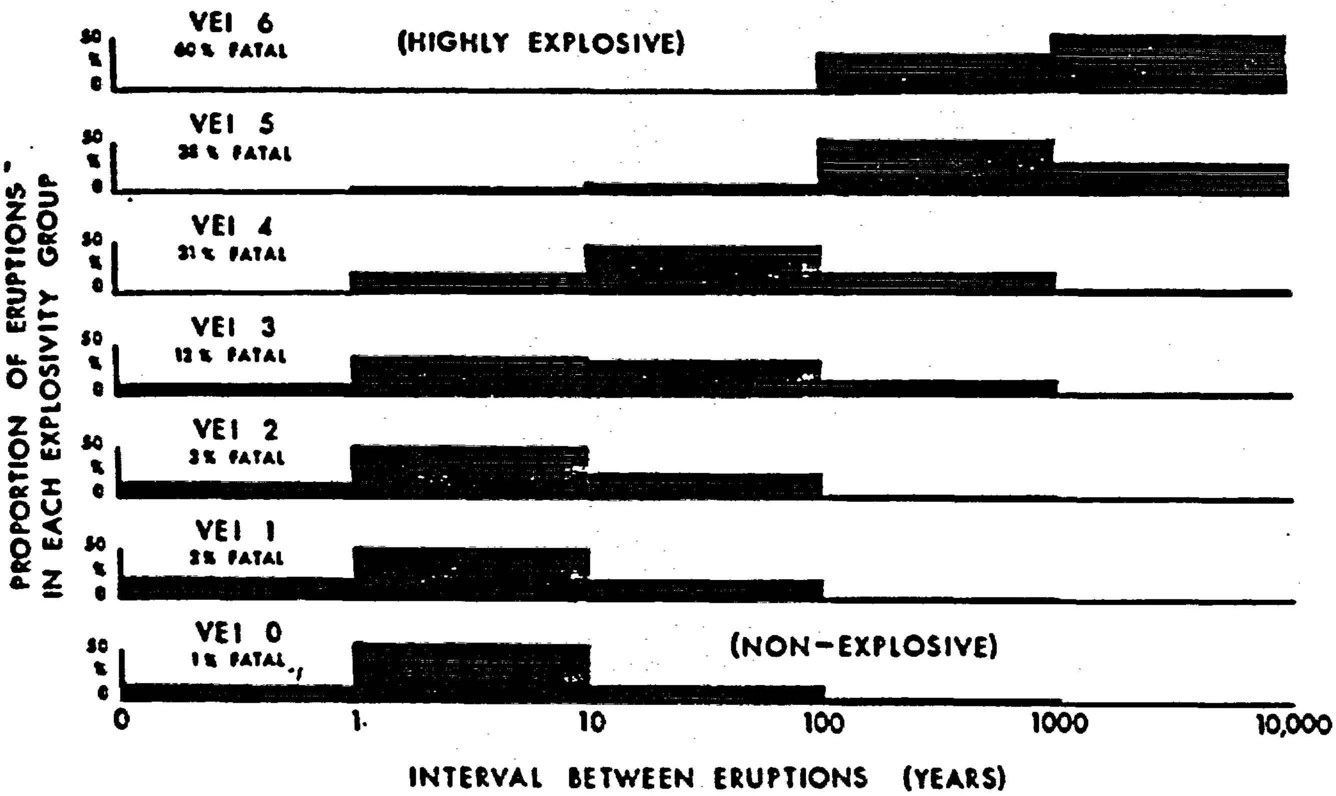

Figure 6-1. Relations between explosivity and time intervals between eruptions (Simkin and others, 1981). Events are groups in each class of "volcanic explosivity" index (VEI) according to the time interval elapsed after the last eruption. The numbers of eruptions in VEI groups 0 to 6 are, respectively, 354, 338, 2882, 617, 102, 19, and 8. For each group, a value is given for the percentage of historic eruptions that have resulted in at least one fatality.

this relation presents a problem in evaluating potential hazards. The longer the period of repose, the less complete will be the geologic evidence of past eruptions, but at the same time, the consequences of renewed activity can be correspondingly greater.

An initial outbreak of volcanism from a hotspot with no record of previous eruptive activity is such a rare event that it is impossible to evaluate its probability. If such an eruption were to occur, it would probably be preceded by centuries of identifiable geophysical phenomena, such as increased seismic activity or heat-flow. For example, a large thermal anomaly under southern California has been identified by seismic tomography. The techniques for identifying large thermal anomalies and bodies of magma have recently been developed to the extent that they provide a means of surveying any region and detecting potentially dangerous conditions. The method has been well described by Iyer (1984). Although Iyer dealt mainly with centers of recent volcanism, he described geophysical methods by which bodies of magma could be located in other regions of potential activity. The significance of these techniques lies in their potential for studying the crust under a particular site and detecting potentially important bodies of magma. Even though interpretation of such anomalies needs refining, the means of detecting them have been developed to the degree that it is safe to assume their presence would be known and a site over such a feature could be avoided.

A second major type of large-scale volcanism is related to dilational faulting and continental rifting. During at least seven episodes, widely spaced between Precambrian and Miocene time, huge outpourings of flood lavas have been discharged from multiple fissures to cover wide areas of the continents of North and South America, Siberia, Greenland, India, and South Africa. The most familiar example is the series of Miocene basalts of the Columbia Plateau, which cover an area of 220,000 km^2 in Oregon, Washington, and Idaho. Individual flows with volumes as great as 1500 km^3 erupted from fissures tens of kilometers in length and, in periods of a week or so, spread for distances of up to 300 km (Williams and McBirney, 1979).

All flood lavas are associated with continental rifting and result from such large-scale tectonic events that they could not occur without many years of conspicuous premonitory phenomena. The fissure eruptions from the central rift of Iceland, though much smaller, are the only modern example that could provide an analog for the past. Icelandic geologists have developed reliable methods of forecasting eruptions of this sort and can recognize the sites of coming eruptions months or even years in advance (e.g., Tarantola and others, 1982). Although a few regions, notably the Rio Grande Rift and the Salton Sea area at the head of the Gulf of California, have been interpreted as zones of recent dilational faulting, they show few signs at this time of evolving into systems capable of generating large-scale eruptions of flood basalts. The problem of evaluating probabilities of eruptions in such regions of more moderate tensional faulting is discussed in the following section.

<u>Sources of Information on Regional Patterns of Volcanism.</u> The information required for probabilistic calculations of volcanic hazards in regions with no historic record of activity comes mainly from regional geological and

geophysical surveys. Field studies are undertaken to find evidence of past activity in the stratigraphic record. With sufficient data on the ages and volcanic character of the rocks, it is possible to establish the frequency of past activity and to predict the nature of future eruptions. In using data obtained in this way, it is important to bear in mind certain limitations that arise from the basic nature of volcanic activity. The most serious of these arise from the following well-recognized relationships.

First, the most powerful volcanic eruptions tend to leave the most widely dispersed and hence the thinnest deposits (Walker, 1982). Because they tend to be light and unconsolidated, the products of very strong explosive eruptions may be quickly eroded and lost. Even the deposits of great historic eruptions are difficult to find only a few decades after they were laid down. Second, as mentioned above, large eruptions tend to be much less frequent than small ones. Hence, in trying to assess the probability of a major eruption, one is dealing with a small number of widely spaced events in the history of a region. Missing even one large eruption results in a seriously distorted statistical record. Finally, the structural edifice of a large explosive volcanic center tends to have inconspicuous relief. Many are low-rimmed calderas buried in their own debris. For this reason, they are less likely to be identified than smaller structures of lesser importance. Thus the available record is not only incomplete, but also biased toward small events, such as eruptions of lava, that leave a more enduring record.

Hence the problem of assessing hazards on a regional scale is basically one of finding the sources and products of past eruptions, determining their ages (see Ch. 4 of this volume), and measuring their extent and volume. Although many major eruptive centers have been identified in the western states, it is difficult to say with assurance that all are known, and even less certain that their eruptive history is well established.

<u>Specific Igneous Centers</u>

This section addresses techniques for determining the potential for igneous activity within the immediate vicinity of a repository. Because repositories are not likely to be sited in close proximity to volcanic centers with a record of historic activity, the methods used to monitor such volcanoes and to forecast consequences of eruptions (e.g., Newhall, 1981, 1982) are largely irrelevant to the question of nuclear-waste disposal and need not be considered here. Although some of the methods of calculating probabilities could be of general use, the methods have limited application to regions of very infrequent activity and few historic data. Nevertheless, the efficiency of monitoring techniques in forecasting eruptions may be an important factor in estimating probabilities, because they will determine the lead time that may be available before an igneous event could disrupt a repository. These techniques could be applied to a variety of types of regions, including those with no record of previous activity, and could be important tools in the future. For example, Adamchuk and others (1984) described a potentially useful means of forecasting volcanism in regions with no recent activity, but the techniques are untested and their reliability in a given region cannot be assessed. Archambault and others (1982) described modern techniques for detecting thermal anomalies associated with potential volcanic activity. Burton (1982) showed how the present state of a large but long-inactive volcanic center can be evaluated by geological and geophysical methods. Tarantola and others (1982) provided an excellent description of the use of seismic methods and strain measurements to forecast volcanic activity, mainly in regions of rifting. Tazieff and Sabroux (1983) collected papers on all aspects of monitoring volcanoes and anticipating the nature of their activity. The collection deals almost entirely with recently active volcanoes, but is the most up-to-date summary of the techniques used to forecast eruptions. The main conclusion is that it is probably safe to assume that no major igneous event could occur, even in a region with no record of recent activity, without premonitory phenomena warning of the impending activity, and that as geophysical techniques are further refined, the lead time provided by these methods will become longer.

Other factors that will enter probabilistic analyses on a local scale are geologic conditions--such as rock properties, ground-water levels, fracture patterns, and geothermal gradient--that can affect the manner in which magma could rise to intrude the repository or erupt close enough to the facility to affect its performance. Examples of the ways in which these data enter probabilistic calculations have been given by Booth (1979); Carr (1974); Crowe, Amos, and others (1982); Crowe, Johnson, and Beckman (1982); Johnpeer and others (1981); Marsh (1981); Vaniman and Crowe (1981); Wilson and Head (1981); and Logan and others (1982). Carr (1974) provided an example of the techniques used to determine the nature of regional stresses in the crust and their relations to past and present centers of volcanic activity. Vaniman and Crowe (1981) showed how studies of geologic structures and the compositions of igneous rocks can be used to interpret the current stage of tectonic and magmatic evolution of a region. The work of Booth, Crowe and his colleagues, Johnpeer and others, Marsh, and Wilson and Head is discussed below. In the more refined studies, probabilities can be zoned and delineated on maps, as shown by Booth (1979) and Westercamp and Traineau (1983). The latter, in a study of a recently active volcano, outlined a method of zoning the magnitudes of different types of volcanic hazards on maps. Westercamp and Traineau also illustrated techniques that can be used to determine the prehistoric eruptive history of a large volcanic complex.

Translating local geological and geophysical conditions into quantitative probabilistic estimates entails theoretical analyses of the factors governing the rise of magma from deep levels and is somewhat speculative. With the current level of understanding of magmatic processes, it is impossible to evaluate how sound these interpretations are likely to be. The next section deals with specific techniques and discusses several examples.

Methods of Estimating Probabilities of Volcanic Hazards

Probabilities of an igneous event occurring within a given distance of a repository site have been calculated by various means. In most instances, the critical factor in the calculation is the frequency of past igneous events within an effective range of the site. The simplest approach is to determine the number and time span of all igneous manifestations that can be assigned ages and to divide one by the other to obtain an average frequency. The probability has then been estimated by one of two methods that are illustrated by the following examples.

Crowe and his co-workers (Crowe, 1980, 1981; Crowe and Carr, 1980; Crowe, Amos, and others, 1982; Crowe, Johnson, and Beckman, 1982; Crowe and others, 1983) have dealt with a region in and around the Nevada Test Site where volcanism has occurred at 14 localities within the past 5 million years. Radiometric dating and paleomagnetic measurements of lavas showed that all 14 events occurred between 0.7 and 2.5 million years ago. The probability of an igneous event affecting the site was calculated from the relation

$$P_{\text{volcanic disruption}} = R \times A \qquad (6\text{-}1)$$

where R is the rate of volcanism and A is an area ratio defined as the area of the repository or the area of an appropriate zone of volcanic disruption, whichever is larger, divided by the area for which the rate of volcanism applies. The studies examined several possible assumptions that can be used in this approach. First, the rate of events obtained from dating eruption products depends on the number of sites found and the area examined. In this case, both the number of events and area were small. Geological reasoning could be used to define the area within which an igneous event was capable of affecting the site, but, because data may be incomplete, it is difficult to know whether the rate represented by the volcanic rocks found in that area is representative. A second, more serious problem involves the nature of the volcanic episode and whether the distribution of events is linked to some other factor that may not have a uniform distribution in time and space.

Smith and Luedke (1984) addressed this latter question in a study of the patterns of distribution of igneous activity throughout the western United States. They concluded that the rate has been increasing for the past million years (Figure 6-2). This increase, detected from broad regional studies, is not taken into account in probability estimates derived from past rates.

Johnpeer and others (1981), in another study dealing with a much larger province, assumed the probability of a future event to have a Poisson-type relation to the number of past events per unit time, and that this relation is given by an equation with the form

$$P = 1 - \exp(-\lambda t) \qquad (6\text{-}2)$$

where P is the probability that at least one eruption will occur in a given time, t, and λ is the average annual rate of igneous events. The assumption of a Poisson probability relation was arbitrary, and, as will be shown later in this same section, was probably invalid. The probabilities of a particular disruptive event were calculated by taking a series of possible consequences of eruptions, assigning probabilities to each, and calculating the final probability as the product of the individual values for the probability of an igneous event and the probabilities of all consequences that are conditional on that event:

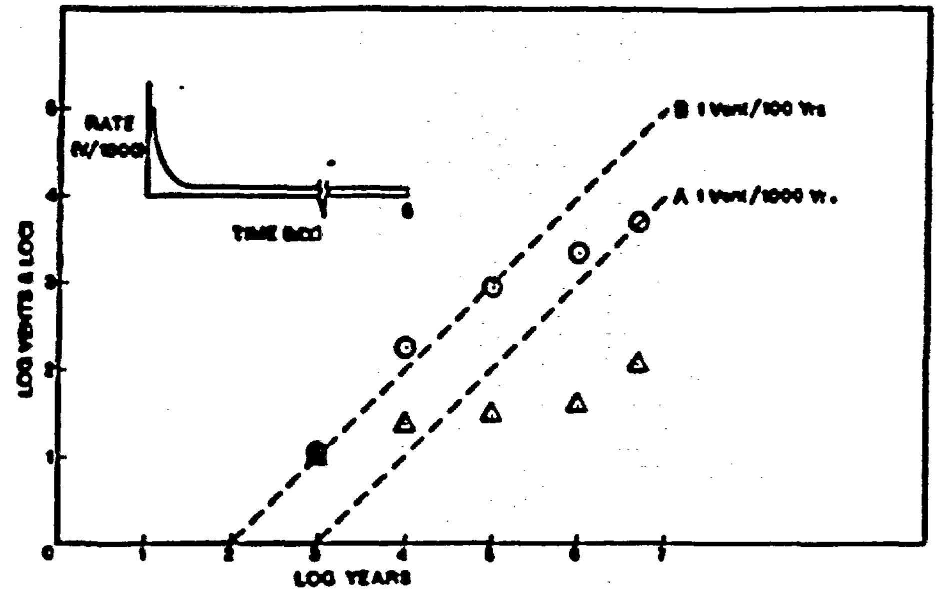

Figure 6-2. Cumulative curves showing volcanic vents and loci active during specific time periods over the past 5 million years, exclusive of the Cascade zone (Smith and Luedke, 1984). The data show an increase in the rate of vent formation within the past million years, particularly over the past 100,000 years. The circles indicate vents, the triangles loci.

$$P_{E/A} = P_{E/D} \bullet P_{D/A} \quad (6\text{-}3a)$$

$$P_{D/A} = P_{D/C} \bullet P_{C/A} \quad (6\text{-}3b)$$

$$P_{C/A} = P_{C/B} \bullet P_{B/A} \quad (6\text{-}3c)$$

where $P_{E/A}$ is the probability of an event dependent on prior events D, C, and B, all of which can follow from A.

When Johnpeer and others used this method for the Hanford Site in Washington, they estimated frequencies of eruptions for three potentially active areas: the central part of the Cascade Range, the Columbia Plateau, and an adjacent part of the Basin and Range province. For example, the frequency for the Columbia Plateau was taken as one event every 2×10^6 years ($\lambda = 5 \times 10^{-7}$/yr). Substituting in Eq. 6-2 gives the probability of an eruption within 10,000 years as

$$P_{(10,000\ yr)} = 1 - \exp(-5 \times 10^{-7} \times 10^4)$$

$$= 1 - \exp(-5 \times 10^{-3})$$

$$= 0.005 \text{ or } 0.5\%$$

Having estimated the probability of an eruption, Johnpeer and others estimated probabilities for each of a series of subsequent conditions, such as the nature and magnitude of the eruption, the probability that it would reach the site or dam the Columbia River, and so on. These "conditional probabilities," each of which is contingent on a preceeding probability, were calculated in the same way as the initial probability. Finally, the probability of a disruptive event affecting the site was obtained by multiplying the eruption probability by all the conditional probabilities. The probabilities of these consequences were estimated from a variety of geologic factors.

For example, one can estimate the range of volumes and areal extents of possible lava flows from previous events. One can then postulate that if one of these types of eruptions were to occur, it would entail the further possibility of damming a major drainage system. A probability for that conditional event would be needed to estimate the probability of flooding at the elevation of the repository. Petrie and others (1981) showed how this exercise can be developed as an interactive computer code.

As Johnpeer and his co-workers (1981) recognized, the most serious deficiency of this approach lies in the temporal distribution of events used to estimate a rate of eruption. More recent work on well documented volcanoes with long records of historic activity (Chester, 1986; Mulargia and others, 1986) has led to differing assessments of the assumption that events have a Poisson probability relation. While eruptions may be random on a short time scale, they are not on the scale of centuries or more, and the probability of a given event is not independent of previous events. On the Columbia Plateau, activity was strongly concentrated in a period of about 10^6 years. In fact, geologists working in the region estimate that at least 99% of the erupted material was discharged during a very brief period 15 million years ago: radiometric age determinations of the products of the main episode are indistinguishable within the precision of the analytical methods (Watkins and Baksi, 1974). In other words, 99% of the eruptive events could have occurred during a period of less than 10^6 years, while the rest were distributed at irregular intervals over the next 14 million years. The "eruption rate" obtained from these data will differ dramatically depending on the time interval used and the way in which the events are distributed within that interval. Because volcanism is so episodic, both locally and globally, this problem will be encountered in almost every province and on every scale of measure. Unless one can define the temporal pattern of events and can say where we are in a cycle at a given time, the probabilistic calculations have little meaning.

There may be ways of dealing with the question of episodicity. The temporal distribution of volcanic events has been studied on several scales, ranging from individual volcanoes to the earth as a whole. The treatment of individual eruptive centers is the most rigorous, because more data are available and the dating of events is more precise. Even though a repository is not likely to be sited in the vicinity of a volcanic center with such a record of historic activity, it is useful to examine the method of analysis, because it could conceivably be applied on time and distance scales relevant to a site in a region of little or no Holocene activity.

Wickman (1966) provided an important statistical analysis of the frequency distribution of eruptions and methods of using such data to estimate the probabilities of activity after differing periods of repose. Compiling data on the timing of events in several provinces and individual eruptive centers, Wickman found several distinctive patterns (Figure 6-3). In some instances, he found a linear relationship between the log of the number of repose periods (or intervals without recorded eruptions) and the durations of these intervals. The differences in the patterns from one volcano to another or even in the record of a single volcano are probably related to local geologic conditions and are poorly understood, but possibly, with sufficient data, this method could be extended to large-scale episodic activity. The studies of Etna are the best example of what can be done with large numbers of reliable data (Mulargia and others, 1985, and references therein).

The number of data that can be obtained for a given region will depend, of course, on local geologic conditions. In many places, previous studies will already have revealed the general level of earlier volcanism, and little additional investigation may be needed. But if much of the geologic record is missing, owing, for example, to extensive erosion, then no amount of geological work will improve the data base needed for probability estimates.

Assuming that a realistic rate could be deduced from detailed geological and geochemical data, probabilities could be calculated for the volcanic hazards at a particular locality using Booth's (1979) method for delineating zones of risk around a known eruptive center (Figure 6-4). Booth calculated the probabilities using a Poisson model, but, as mentioned above, the Poisson distribution may not in all cases be appropriate.

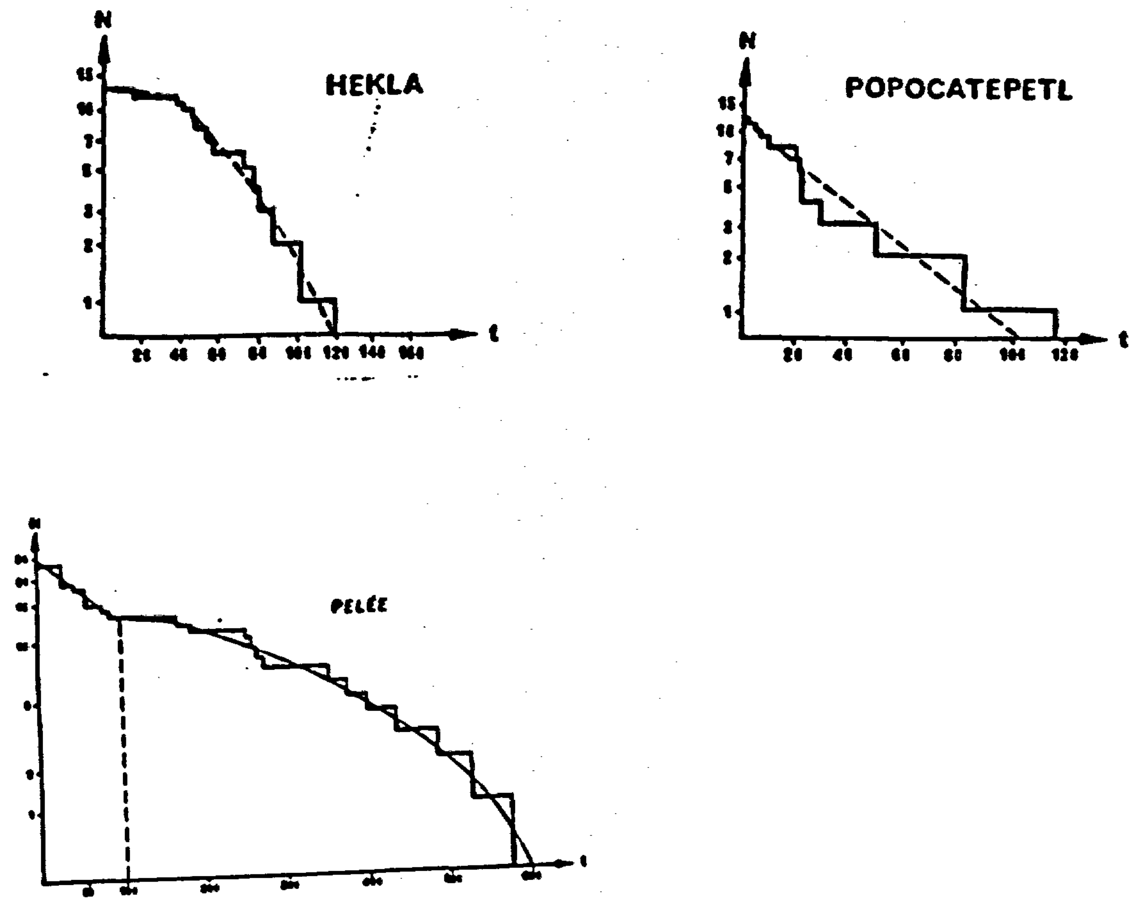

Figure 6-3. Wickman diagrams for three large volcanoes with long records of eruptive activity (Wickman, 1966; Westercamp and Traineau, 1983). N is the number of repose periods, and t is the length of the period of repose in years. The probability of an eruption after a given period of quiet is proportional to the negative slope of the curve. In theory, a similar diagram could be constructed for any volcanic system for which there are sufficient data.

Another type of probabilistic calculation treats the problem of magma rising through existing or newly established conduits. The rise of magma from a source in the mantle or deep crust can be analyzed in terms of the physics of flow of a viscous fluid through a colder medium. The probability of magma rising a given distance depends mainly on its viscosity and rate of heat loss to its surroundings. Several persons have analyzed the problem in detail (e.g., Wilson and Head, 1981; Marsh, 1981, 1984; Hardee, in press). The data needed for such an analysis include measurements of the thermal gradient, estimates of the probable width and length of fissures, probable magma compositions, and ground-water levels and permeabilities. In general, a region with a high geothermal gradient, particularly where the crust has been heated by previous intrusions, is more vulnerable to magmatic intrusions, because of the reduced heat loss from the rising magma to the country rock. Silica-rich magmas have greater viscosity and rise more slowly than silica-poor magmas and are less likely to rise to shallow levels without being frozen. Statistical studies confirm these relations, and enough data are available to permit a sophisticated analysis of the probability that a given type of magma will reach near-surface levels. Marsh (1981, 1984) has provided graphical solutions for estimating the probability that a magma of any common composition will erupt (Figure 6-5), and Hardee (in press) has used the same approach to estimate the rate and distribution of new magmas rising into the crust in the western US.

Possible Interactions between Volcanic Processes and Waste Repository

A number of workers have discussed the potentially damaging effects of volcanism. Kates (1978) dealt with methods of evaluating all types of natural hazards, but did not stress very rare volcanic events. Bailey and others (1983) outlined regions of past and possible future volcanism in the US and measures to alleviate various types of volcanic hazards. Martin and Davis (1981) edited a symposium volume dealing with methods of anticipating and alleviating volcanic hazards. They included individual reports and accounts of round-table discussions of a great variety of hazards. Tilling and Bailey (1984) reviewed volcanic hazards in regions of active volcanism in the US and discussed the problem of dealing with potential hazards in regions with little or no recent activity.

In addition, a few workers have attempted to predict the damage that might occur if volcanism takes place through or in the immediate vicinity of a HLW repository. Crowe (1980) evaluated the disruptive effects of igneous activity on a repository and indicated ways in which these effects might be reduced by judicious siting and by adapting the geometry of the facility to the structural trends of the region. Crowe (1981) also outlined the possible ways in which an igneous intrusion with or without a surface eruption could result in a release to the environment. Crowe, Amos, and others (1982) showed how the possibility of disrupting a repository can be estimated from the relative sizes of typical feeder dikes and the area of the repository. Logan and others (1982) calculated potential releases of radioactive waste, exposures to human beings, and health effects that might follow the intersection of a repository in southern Nevada by feeder dikes for a basaltic cinder cone.

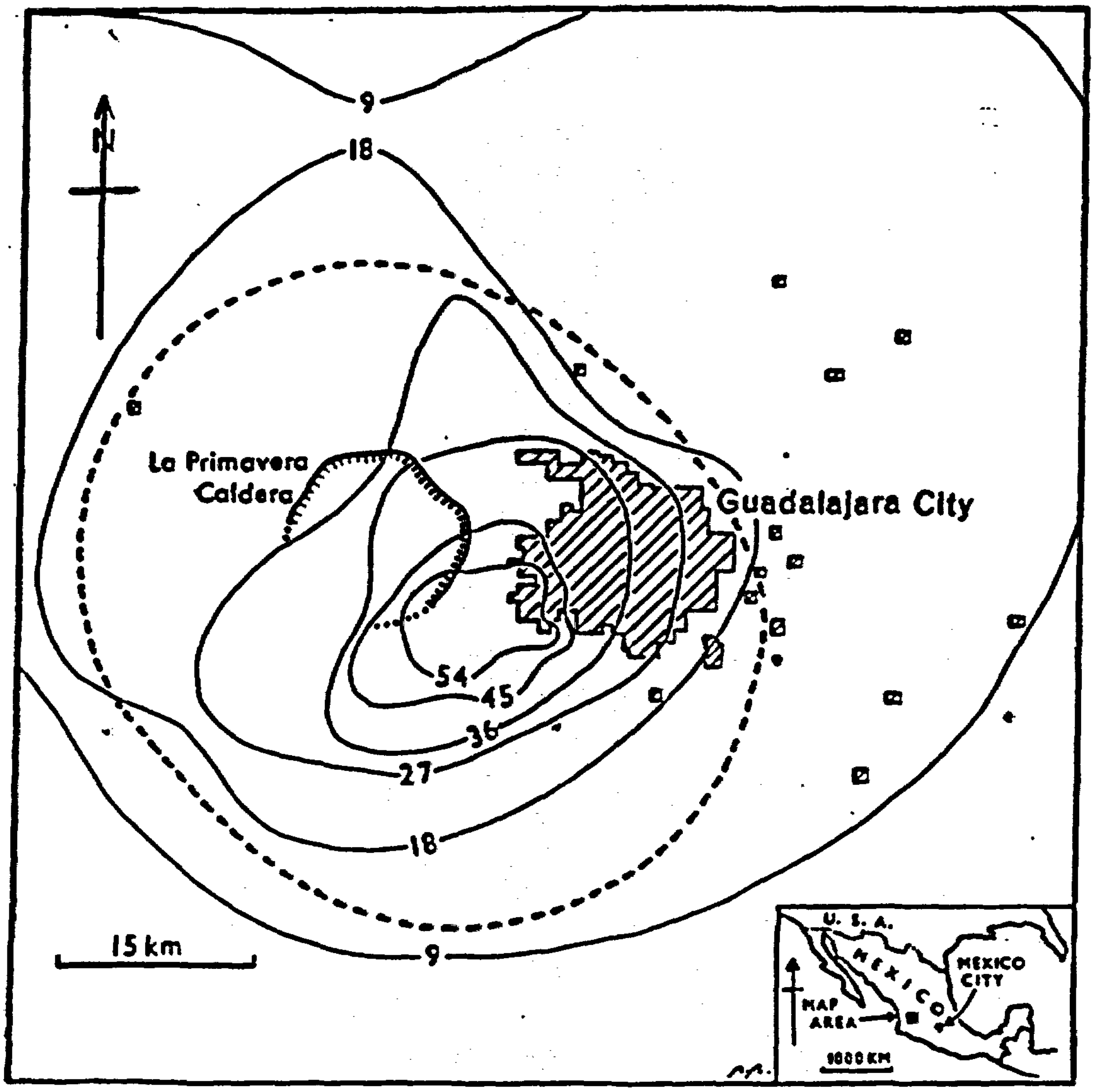

Figure 6-4. Volcanic risk map for the area around Guadalajara, Mexico (Booth, 1979). The isopleths show the percentage probability that the areas they enclose will be buried by over one meter of ash during the next major eruption. The dashed line encloses the area of risk from lithic missiles at least 0.1 m in diameter.

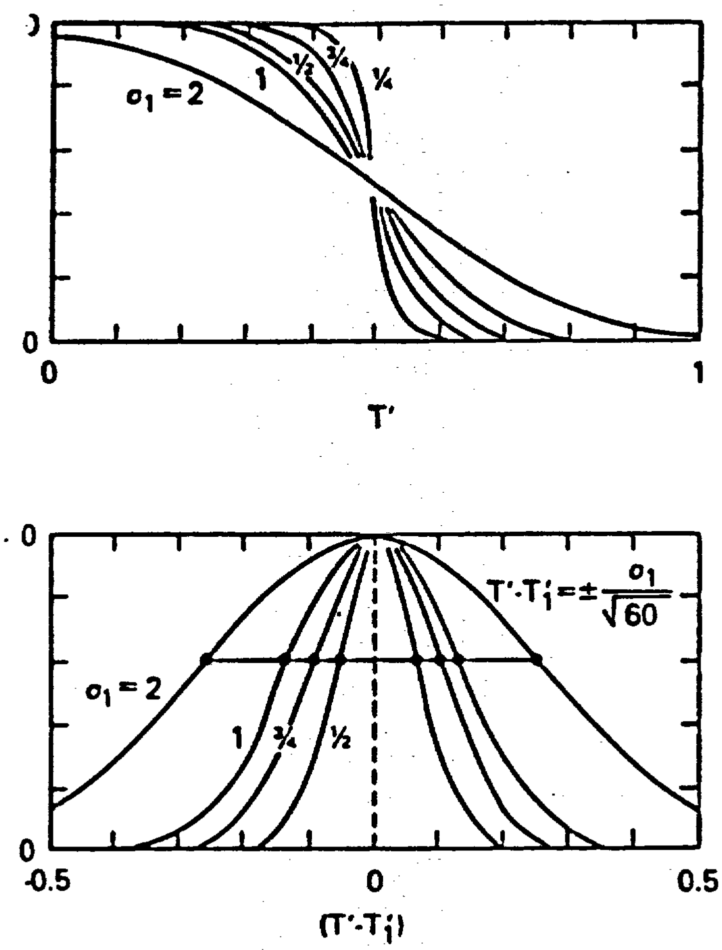

Figure 6-5. A plot of the fraction of crystallization (above) against dimensionless temperature between the liquidus and solidus can be converted to the probability, P_T, that a magma with a given crystallization curve will reach the surface before it becomes too viscous to flow (Marsh, 1981). In the lower diagram, curves of P_T are shown for a variety of such magmas. The form of the curves is defined by a function, sigma, which is essentially the slope of the crystallization curve in the upper diagram.

Conclusions and A Currently Feasible Approach

The foregoing review has shown that probability estimates for igneous events capable of affecting a repository could have a wide range of reliability depending on the character of the site and the degree to which its tectonic and magmatic evolution can be projected into the future. Calculations can be very precise for simple, well documented volcanic centers with long records of historic activity, but much less precise for structurally complex regions with older and less frequent eruptions.

Even though it is unlikely that a repository would be located close to recently active volcanoes, the techniques for calculating probabilities for large, historically active volcanic centers, such as Etna, Kilauea, or Mauna Loa, can be adapted to older eruptive centers with no historic activity but an extended record of eruptions during the past 10^6 years or so. The farther one goes back in time, of course, the more difficult it is to make allowances for the proportion of the record lost through wind dispersal of ash or through erosion. Nevertheless, if enough age determinations can be obtained for previous events, it is possible to establish the frequency distribution of eruptions in time and space and to detect patterns of eruptive behavior. With this information, the methods developed by Wickman (1976) can be used to analyze the probabilities of a given trend extending into the future.

The most serious problem with this technique is that events can seldom be assumed to have a random distribution. In almost every instance in which volcanism has been thoroughly dated over periods of more than a few centuries, temporal trends have been found to be episodic, and both the timing and character of individual events is often a function of the preceding repose period and earlier history of the system. It is essential, therefore, to identify the present geological state of the region and the long-term trends of its magmatic evolution.

Even though the immediate vicinity of the site may have little or no record of Holocene activity, it could be affected by future eruptions associated with large-scale tectonic features migrating through a broader region. For this reason, it is crucial to understand the regional environment of the site and the manner in which volcanism has been related to propagating zones of faulting and migrating thermal anomalies. If rates and directions can be assigned to these features, they can be projected into the future, and the nature and spacing of igneous events that could break out in the vicinity of the site can be anticipated.

Analysis of these geological relations and the degree to which a possible event would result in dispersal to the environment will entail so much expert judgment that, in the end, the considered opinion of informed specialists may be more realistic than numerical calculations based on incomplete data and uncertain projections of the tectonic and magmatic regime. This is particularly true of tectonically stable regions, such as much of the eastern US, where no Cenozoic igneous events have been detected. An attempt to calculate probabilities of a random eruption or intrusion, such as those that have occurred at widely spaced intervals in the past, would have less value than a considered expert opinion based on a thorough analysis of the geologic setting and comparisons with similar geologic conditions elsewhere.

References

Adamchuk, Y. V., Y. P. Fedorovski, P. P. Firstov, K. P. Kim, A. V. Storcheus, and P. P. Titov, 1984, "A Method for Continuous Measurement of the Bulk Activity of Emanations for Predicting Earthquakes and Eruptions of Volcanoes using Plastic and Combined Scintillational Detectors," Inst. Atomic Energ. Prepr., 3894/14, 31 pp.

Archambault, C., G. Scarpinata, J. Stoschek, and J. C. Tanguy, 1982, "Analyse et surveillance Thermique de volcans actifs," Bull. PIRPSEV, No. 66, 27 pp.

Bailey, R. A., P. R. Beauchemin, F. P. Kapino, and D. W. Klick, 1983, The Volcano Hazards Program: Objectives and Long Range Plans, Open-file Report, US Geological Survey, 35 pp.

Booth, B., 1979, "Assessing Volcanic Risks," Jour. Geol. Soc. London, vol. 136, p. 331-340.

Burton, B. W., 1982, Geologic Evolution of the Jemez Mountains and Their Potential for Future Volcanic Activity, Contract Report W-7405-ENG-36, Los Alamos National Laboratory, Los Alamos, NM, 35 pp.

Carr, W. J., 1974, Summary of Tectonic and Structural Evidence for Stress Orientation at the Nevada Test Site, Open-file Report 77-176, US Geological Survey, 57 pp.

Chester, D. K., 1986, "Discussion: A Statistical Analysis of Flank Eruptions on Etna Volcano," Jour. Volc. Geoth. Research, in press.

Crowe, B., 1980, Disruptive Event Analysis: Volcanism and Igneous Intrusion, Contract Report No. AC06-76RL01830, Battelle Pacific Northwest Laboratory, 45 pp.

Crowe, B., 1981, "Assessment of Effectiveness of Geologic Isolation Systems," WISAP Release Scenario Analysis Workshop, Sept. 13-15, 1979, Seattle, WA.

Crowe, B., and W. J. Carr, 1980, Preliminary Assessment of the Risk of Volcanism at a Proposed Nuclear Waste Repository in the Southern Great Basin, Open-file Report 80-375, US Geological Survey, 14 pp.

Crowe, B., M. E. Johnson, and R. J. Beckman, 1982, "Calculation of the Probability of Volcanic Disruption of a High-Level Radioactive Waste Repository Within Southern Nevada, USA," Radioactive Waste Management, vol. 3, p. 167-190.

Crowe, B., R. Amos, F. Perry, S. Self, and D. Vaniman, 1982, Aspects of Possible Magmatic Disruption of a High-Level Radioactive Waste Repository in Southern Nevada, Report 9326-MS, Los Alamos National Laboratory, Los Alamos, NM, 43 pp.

Crowe, B., S. Self, D. Vaniman, R. Amos, and F. Perry, 1983, "Aspects of Potential Magmatic Disruption of a High-Level Radioactive Waste Repository in Southern Nevada," Jour. Geol., vol. 91, p. 259-276.

Hardee, H. C., in press, "Replenishment Rates of Crustal Magma and Their Bearing on Potential Sources of Thermal Energy," Jour. Volc. Geoth. Research.

Iyer, H. M., 1984, "Geophysical Evidence for the Locations, Shapes, and Sizes, and Internal Structures of Magma Chambers Beneath Regions of Quaternary Volcanism," Phil. Trans. Royal Soc. London, vol. A 310, p. 473-510.

Johnpeer, G. D., D. Miller, and G. G. Goles, 1981, "Assessment of Potential Volcanic Hazards: Pasco Basin, Washington," Contract Report AC06-77RL01030, Rockwell International Corp., 35 pp.

Kates, R. W., 1978, Risk Assessment of Environmental Hazard, Wiley, New York, 137 pp.

Kennett, J. P., and R. C. Thunell, 1975, "Global Increase in Quaternary Volcanism," Science, vol. 187, p. 497-503.

Kennett, J. P., A. R. McBirney, and R. C. Thunell, 1977, "Episodes of CenozoicVolcanism in the Circum-Pacific Region," Jour. Volc. Geoth. Research, vol. 2, p. 145-163.

Logan, S. E., R. L. Link, H. S. Ng, F. A. Rockenbach, and K. J. Hong, 1982, Parametric Studies of Radiological Consequences of Basaltic Volcanism, SAND81-2375, Sandia National Laboratories, Albuquerque, NM, 216 pp.

Marsh, B. D., 1981, "On the Crystallinity, Probability of Occurrence, and Rheology of Lava and Magma," Contrib. Min. Petrol., vol. 78, p. 85-98.

Marsh, B. D., 1984, "Mechanics and Energetics of Magma Formation and Ascension," Explosive Volcanism: Inception, Evolution, and Hazards, National Academy Press, p. 67-83.

Martin, R., and J. F. Davis, eds., 1981, Status of Volcanic Prediction and Emergency Response Capabilities in Volcanic Hazard Zones of California, California Div. Mines and Geology, 275 pp.

Mulargia, F., S. Tinti, and E. Boschi, 1985, "A Statistical Analysis of Flank Eruptions on Etna Volcano," Jour. Volc. Geoth. Research, vol. 23, p. 263-272.

Mulargia, F., S. Tinti, and E. Boschi, 1986, "Reply to Discussion of D. K. Chester," Jour. Volc. Geoth. Research, in press.

Newhall, C. G., 1981, "Probabilistic Hazard Assessment at Mount St. Helens," in M. Kent, ed., New Horizons in Engineering Geology, p. 47-48.

Newhall, C. G., 1982, A Method for Estimating Intermediate- and Long-Term Risks from Volcanic Activity, with an Example from Mount St. Helens, Washington, Open-file Report 82-396, US Geological Survey, 58 pp.

Niccum, M., K. M. Cline, and M. Jackson, 1980, "Volcanic and Seismic Hazards on the Snake River Plain, Idaho," Ann. Symp. Eng. Geol. and Soils Eng., Boise State Univ., Boise, Idaho, 81 pp.

Petrie, G. M., J. T. Zellmer, J. W. Lindberg, and M. G. Foley, 1981, Geologic Simulation Model for a Hypothetical Site in the Columbia Plateau, PNL-3542, Batelle Pacific Northwest Laboratories, 603 pp.

Scott, W. E., 1978, Hazardous Volcanic Events and Assessment of Long-Term Volcanic Hazards, Open-file Report, US Geological Survey, p. 447-498.

Simkin, T., and L. Siebert, 1982, "Large Historic Explosive Eruptions: How Much Warning?" Eos. Trans. Amer. Geophys. Union, vol. 63, p. 459.

Simkin, T., and L. Siebert, 1984, "Explosive Eruptions in Space and Time: Duration, Intervals, and a Comparison of the World's Active Volcanic Belts," Explosive Volcanism: Inception, Evolution, and Hazards, National Academy of Science, p. 110-121.

Simkin, T., L. Siebert, L. McClellend, D. Bridge, C. Newhall, and J. H. Latter, 1981, Volcanoes of the World, Smithsonian Institution, Hutchinson Ross, 233 pp.

Smith, R. L., and R. G. Luedke, 1984, "Potentially Active Volcanic Lineaments and Loci in Western Conterminous United States," Explosive Volcanism: Inception, Evolution, and Hazards, National Academy of Science, p. 47-66.

Tarantola, A., E. Trygvasson, and A. Nercessian, 1982, "La prevision volcanique ou sismique traitee comme un probleme inverse," Bull. PIRPSEV, No. 61, 19 pp.

Tazieff, H., and J. C. Sabroux, eds., 1983, Forecasting Volcanic Events, Elsevier, 635 pp.

Tilling, R. I., and R. A. Bailey, 1984, "Volcano Hazards in the USA," in S. A. Fedetov, ed., Earthquakes and Geological Hazard Prediction, 27th Internat. Geol. Congress, Moscow, vol. 27, p. 106-118.

Vaniman, D., and B. Crowe, 1981, Geology and Petrology of the Basalts of Crater Flat: Applications to Volcanic Risk Assessment for the Nevada Nuclear Waste Storage Investigations, Contract Rept. W-7405-ENG-36, Los Alamos National Laboratory, 68 pp.

Walker, G. P. L., 1982, "Volcanic Hazards," Interdisciplinary Sci. Rev., vol. 2, p. 148-157.

Watkins, N. D., and A. K. Baksi, 1974, "Magneto-Stratigraphy and Oroclinal Folding of the Columbia River, Steens and Owyhee Basalts in Oregon, Washington, and Idaho," Amer. Jour. Sci., vol. 274, p. 148-189.

Westercamp, D., and H. Traineau, 1983, "The Past 5,000 Years of Volcanic Activity at Mt. Pelee, Martinique (F. W. I.): Implications for Assessment of Volcanic Hazards," Jour. Volc. Geoth. Research, vol. 17, p. 159-185.

Wickman, F. E., 1966, "Repose-Period Patterns of Volcanoes," Arkiv for Mineralogi och Geologi, vol. 4, p. 291-352.

Williams, H., and A. R. McBirney, 1979, Volcanology, Freeman and Cooper, 397 pp.

Wilson, L., and J. W. Head, 1981, "Ascent and Eruption of Basaltic Magma on the Earth and Moon," Jour. Geophys. Research, vol. 86, p. 2971-3001.

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