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Uncertainties in Long-Term Repository Performance due to the Effects of Future Geologic Processes

A. L. Sjoreen
D. C. Kocher

Prepared for the
U.S. Nuclear Regulatory Commission
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UNCERTAINTIES IN LONG-TERM REPOSITORY PERFORMANCE DUE TO THE EFFECTS OF FUTURE GEOLOGIC PROCESSES

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UNCERTAINTIES IN LONG-TERM REPOSITORY PERFORMANCE DUE TO THE EFFECTS OF FUTURE GEOLOGIC PROCESSES

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ABSTRACT

This report discusses the nature of uncertainties in predicting the long-term performance of geologic repositories for the disposal of high-level radioactive wastes that result from the effects of future geologic processes. This type of uncertainty in long-term repository performance arises from uncertainties in (1) determining current rates of geologic processes at specific sites, (2) predicting process rates over long time periods in the future, and (3) predicting the effects of future geologic processes on the waste-isolation capabilities of a repository. The qualitative and judgmental nature of predictions of future geologic processes and their effects on repository performance is emphasized. However, since significant geological changes generally occur over time periods of 100,000 years or more, it should be possible to select repository sites which are sufficiently stable that geologic processes should have no significant effects on waste isolation over a period of 10,000 years.

1. INTRODUCTION

The concept of permanent disposal of high-level radioactive wastes in deep geologic repositories is based on the need to isolate the waste from the biosphere for long periods of time and the belief that emplacing the waste far below the Earth's surface will achieve this objective. However, changes can occur in geologic environments over long periods of time and these changes could have detrimental effects on the waste-isolation capabilities of a repository. Thus, in the process of selecting and licensing repository sites, it will be important to estimate the effects of geologic processes on long-term repository performance.

Estimates of the effects of most geologic processes on long-term repository performance cannot be obtained by direct observation of changes in the geologic environment; nor can such estimates be obtained through laboratory studies. Rather, these estimates require the application of scientific judgment to geologic data. These data rarely are sufficiently complete to define unambiguously the processes being studied, so that the processes are likely to be subject to different interpretations. It is desirable to select repository sites for which the predicted range of effects of geologic processes should not adversely affect the predicted radiological consequences of waste disposal. In order to demonstrate that this will likely be the case, one must decide which processes could be important at a given site, what the likely range of process rates will be, and what effects this range of process rates might have on the waste-isolation capabilities of the site.

In order to appreciate the current limitations in our ability to estimate the long-term effects of geologic processes on repository performance, one must understand the methods by which such estimates are obtained. The types of geologic analysis which are appropriate for determining the effects of relatively rapid processes over short time periods, such as determining slope stability or predicting fault movement, are not necessarily applicable to determining the effects of slow processes over long time periods, such as predicting regional uplift or the effects of global climate changes. The nature of geologic data and geologic analysis is discussed in Section 2 of this report.

Generic rates of geologic processes can be estimated using a general knowledge of geologic history. These rates can be used to estimate the period of time over which each process could affect waste isolation. Section 3 presents generic estimates of geologic process rates and a discussion of their usefulness and uncertainties.

The effects of geologic processes on long-term repository performance can be predicted either by mathematical models or by studies of natural geologic systems (i.e., natural analogs). The uncertainties in predictions obtained from mathematical models result from the fact that both the input data and the selection of important processes and process interactions for inclusion in the models are essentially subjective judgments. Models have been developed which allow for changes in the geologic environment due to natural causes. As far as we are aware, however, only the Geologic Simulation Model[1] attempts to treat simultaneously the effects of all likely geologic processes. Predictions of repository performance based on studies of natural analogs require that the similarities and differences in the environments of the analog and the actual site be understood and that the present geologic environment of the site be reasonably similar to the past environment of the analog. The usefulness of both mathematical and natural analog models in predicting the future geologic environment and its effects on waste isolation is discussed in Section 4.

Section 5 presents some concluding remarks on the nature of uncertainties in predicting future geologic processes and their effects on long-term repository performance.

2. GEOLOGY AS A PREDICTIVE SCIENCE

In order to appreciate the nature of predictions of future geologic environments and the uncertainties associated with such predictions, it is useful to have an understanding of the types of geologic data that are available and the methods by which geologists interpret the data. Geologists traditionally have sought to determine the nature of past natural processes by observing their cumulative effects at the present time, but have not sought to predict the effects of processes acting in the future. Geologists usually have attempted to predict far-future geologic conditions only in a global sense, e.g., predicting the relative positions of crustal plates, and such predictions generally are considered speculative.

The extent to which geology has predictive capabilities is not resolved even among geologists (e.g., see Refs. 2 and 3). While the ability of geologists to predict discrete events, such as earthquakes and volcanic eruptions, which may occur over the next few months or years is improving, it is not clear that there have been comparable improvements in the ability to predict the effects of slow, continuous processes at a particular site over time periods of thousands of years or more.

The need for methods of safe disposal of highly radioactive wastes certainly has been one of the most important driving forces behind the increased interest in geology as a predictive science. In fact, the first book on predictive geology[4] is devoted almost entirely to radioactive waste disposal in geologic media. The application of predictive geology to radioactive waste disposal focuses on the need to describe the effects of geologic processes over long time periods and at specific locations of relatively small spatial extent. Predictions of long-term effects at a specific site must be based largely on site-specific data on past geologic processes and their effects. Even for a well-studied site, however, the data likely will be incomplete and subject to a variety of interpretations. When geologists have very different backgrounds and biases, their interpretations may be not only quite different but also irreconcilable. For example, on the basis of the geologic data which have been obtained at the Sterno site in Sweden, one geologist has concluded that extensive regions of low hydraulic conductivity and chemically reducing conditions exist at the depth of a repository, and these conditions are not likely to be affected by future climate changes or tectonic activity over the time period required for waste isolation.[5] On the basis of the same evidence, however, another geologist has concluded that the geologic environment at this site is much more dynamic than generally believed and that extensive fracturing, faulting, and seismic activity are likely during the next ice age, so that the site cannot be regarded as suitable for safe waste disposal.[6] Resolution of this type of controversy may be an important feature of the licensing process for a repository at any site.

An understanding of the sampling strategy used in a geologic study is very important when evaluating the conclusions drawn from the study. Those rocks which are available to be sampled at or near the Earth's surface are those which have been exposed through erosion or faulting. Historically, samples taken from the subsurface tend to have been obtained from areas of high resource potential, because of the expense of drilling and mining. In any study, sampling locations usually are not selected randomly; nor is the sampling scheme designed to determine all the types of geologic data for a site. Sampling locations are selected with the intent of resolving the questions relevant to the particular study.

The number of samples that are available for a particular study may be very limited and will depend on the size of the objects being investigated. The samples of interest could be, for example, rock outcrops, pieces of rock, or mineral crystals. If one is studying the mechanical properties of salt crystals, then one can obtain many crystals for study. However, if one is studying how salt beds have reacted to regional stresses, then one has a much more limited number of available samples. As the size of the objects under study increases, the differences between them begin to outweigh the similarities and it becomes more difficult to draw conclusions based on the whole sample which could be applied to other similar objects. For example, a salt crystal has a fixed crystallographic shape and a sample of crystals can be selected on the basis of chemical purity. However, a salt bed has a shape that is determined by its geologic history and is expected to contain at least small amounts of other minerals. Conclusions based on the study of a crystal of salt can be regarded as true for all salt crystals, but conclusions based on the study of a bed of salt can only be applied to other salt beds if they are known to have similar geologic histories and similar compositions.

The time period of interest for waste isolation, which is quite short on a geological time scale, limits the applicability of available data on geologic processes. Direct observation of geologic processes over thousands of years is impossible. Very slow processes have clearly observable effects only after hundreds of thousands or millions of years. Old rocks have undergone many interacting processes which probably have not been continuous or acting at a constant rate over the lifetime of the rocks. Therefore, it may not be valid to extrapolate process rates over short time periods in the future on the basis of observations of average effects over long time periods in the past.

The geologic record is inherently incomplete because some geologic processes can erase the effects of past processes. For example, erosion has altered and moved large volumes of rock and thereby erased the evidence of the processes that originally formed the rock. Tectonic processes and metamorphism also can severely alter the physical state of rocks. Geologists interpret the available data with the implicit understanding that the data are not complete and are subject to a variety of interpretations.

The geologic history of an area usually is determined by relating the observed features of the area to analogous features of other areas with the assumption that geologic features with similar appearance have similar origins. Geologists develop multiple working hypotheses in an attempt to determine all reasonable sequences of processes that could have produced the observed rocks, and they then collect additional data to eliminate all but the most reasonable hypothesis. For example, if a sequence of three sedimentary units is observed at one location and the middle unit is missing at a nearby location, this difference could be explained by three hypotheses: (1) the middle unit was never deposited at the second location; (2) the middle unit was deposited and subsequently eroded entirely at the second location; or (3) one or both of the sequences have been altered by movement of a nearly horizontal fault. The geologist then would search for faults and erosion surfaces in the area of the two sites in order to determine the most reasonable interpretation of the geologic data.

The assumption that geologic process rates which are inferred from the geologic record provide the best estimate of future geologic process rates may not always be valid. Mankind has had a significant impact on the surface of the Earth, and this impact can affect the rates of natural processes. For example, the sediment load that is currently carried by rivers entering the Atlantic Ocean has been estimated to be about five times greater than it would be without the intervention of mankind.[7] Another example is the possibility that climatological effects of increases in atmospheric CO_2 due to the burning of fossil fuels will disrupt the current pattern of glacial cycles.

The accuracy of estimates of geologic process rates that are obtained from evidence in the geologic record can be no greater than the accuracy with which the dates of the beginning and ending of the process action are known. There are basically two kinds of methods for estimating ages of rocks. First, relative ages of rocks can be estimated from the fossils contained in them and from physical relationships of the rock units. For example, in sequences of sedimentary rocks, the lower rocks are assumed to be older than the upper ones. Also, faults and igneous intrusions must be younger than the rocks in which they are contained. Second, absolute ages of rocks can be estimated from radiometric dating. Radiometric ages of rocks are determined from the ratios of the concentrations of long-lived radionuclides and their stable daughter products,[7] such as $^{87}Rb/^{87}Sr$ and $^{40}K/^{40}Ar$. There are situations, however, in which rock ages cannot be estimated reliably, e.g., when there is insufficient fossil and structural evidence or a rock chemistry which makes radiometric dating difficult. In these cases, estimates of process rates and durations are very imprecise. Errors in estimates of rock ages are often significant compared with the time scale of interest for waste isolation.

The particular field and laboratory methods that are used to determine which past geologic processes have produced the present geologic environment are specific to the subdiscipline of geology being employed and are not discussed here. However, all of these methods rely on a few basic geological principles. One of these principles states that the structure of a geologic feature and the processes which formed that feature must have compatible symmetries. For example, because sediments are deposited in horizontal layers, any sedimentary rocks that are not horizontal must have been acted upon by a force other than gravity. This is called the principle of original horizontality. Another basic geologic principle, called uniformitarianism, states that the types of natural processes acting today are the same as those which have acted throughout geologic time.

Geologists make extensive use of other scientific disciplines. Interpretations of the geologic history of an area are based not only on data gathered in the field, but also on laboratory experiments such as those which define the limits of the conditions under which specific rock types and minerals can form. The uncertainty in a geochemical or geophysical analysis of a geologic problem is a combination of the uncertainties inherent in the chemical or physical methodologies used and the uncertainties inherent in the geologic aspects of the problem. For example, the details of material properties and chemical interactions that are studied in the laboratory usually focus on chemically pure minerals, rather than on multi-mineralic rocks. This is clearly appropriate, since one must first comprehend the simpler systems before evaluating the more complex ones. This is also the reason why there is so much more basic knowledge about the mineral salt (NaCl) than about the rocks basalt, granite, tuff, or shale. When applying information obtained from other scientific disciplines to real geologic systems, one must take into account the greater complexity of natural geologic conditions compared with those in the laboratory.

3. UNCERTAINTIES IN ENVIRONMENTAL CHANGES DUE TO GEOLOGIC PROCESSES

3.1 Introduction

Future changes in the geologic environment due to geologic processes and the rates at which these processes act are difficult to estimate precisely. Geologic process rates are sufficiently slow that the assumption of an unchanging geologic environment is probably valid for geologically short periods of time at a repository site that has been chosen for its stability. In the surface environment, geologic changes can probably be ignored for a few thousand years. In the subsurface environment, geologic processes probably will have negligible effects for a few tens of thousands of years. Any geologic process can have significant effects over millions of years or more. For time periods between thousands of years and a million years, the different processes must be considered individually. Of course, each site must be considered individually as well.

Estimating the uncertainty in predicting the effects of geologic processes on long-term repository performance is a two-step process. First, one must estimate the maximum and minimum magnitude of the expected changes in the geologic environment and the magnitude which is considered most likely. Second, one must estimate the effects of this range of environmental changes on long-term repository performance. The first part of the problem is the more tractable, because it involves only an analysis of geologic history and does not consider the effects of the presence of the repository. The second part of the problem involves determining the behavior of radioactive waste which has been added to the natural system, and one must make determinations of the extent to which the repository and the waste perturb the natural system and the effectiveness of the repository itself for containing the waste. The interactions between the repository and the natural geologic environment are not discussed in this paper.

In predicting future geologic changes based on studies of geologic history, one must keep in mind that not all past geologic changes have left clear evidence for present interpretation. For example, past groundwater recharge and discharge areas may not be detectable from present conditions. Also, fracture systems could open and close, thus changing flow paths temporarily without leaving any evidence of this change.

3.2 Estimates of Generic Geologic Process Rates

Both generic and site-specific data will be needed to describe geologic processes and their effects on the geologic environment. Generic data can be useful in several ways. First, generic estimates of process rates tend to be either expected rates for a particular type of geologic environment or maximum rates for any geologic environment. Thus, if any process rate at a site approaches the generic maximum, the site would be considered very active geologically. This does not necessarily mean that the site is unsuitable for radioactive waste disposal, but it may make the selection of the site more difficult to defend. Second, if it can be shown that the maximum generic rates do not have significantly adverse effects on waste isolation, then one can assume that changes in the natural environment at a particular site will not increase the overall uncertainty in predicting long-term repository performance. Third, generic process rates indicate the time scale over which different processes may become important. Very slow processes will have significant effects only over very long time periods.

The information that is needed to assess the importance of individual geologic processes can be divided into the following five categories: (1) the rates of continuous processes, (2) the recurrence interval for discrete events, (3) the duration of processes, (4) the volume over which a process acts, and (5) the nature of the process interactions. Published estimates of process rates, recurrence intervals, and process durations are summarized in Tables 1-3, respectively; these data are primarily order-of-magnitude estimates. The volume over which a process acts is site-specific and is not treated

Table 1. Geologic process rates[a]

Process	Range (cm/yr)	Average value (cm/yr)
Glacial advance and retreat	$200\text{-}10^6$	1,000
Crustal plate motion	1.5-16	3
Rate of fault movement	0.1-7	1
Regional uplift and subsidence	0.00003-4	1
Rate of sea level change	0.1-1.0	1
Salt diapirism (vertical intrusion)	0.003-0.2	0.1
Salt dissolution	0.005-0.02	0.01
Stream erosion	0.0002-0.1	0.01
General erosion		0.001

[a] Data from Refs. 7-9

Table 2. Recurrence interval of geologic events[a]

Event	Recurrence interval (years)
Volcanic eruption, earthquakes	10^0-10^2
Glacial episode	10^4-10^5
Basalt flows on Columbia Plateau	10^6 or less
Pluton implacement in the Sierra Nevada Batholith, California	10^6-10^7

[a] Data from Refs. 7-9

Table 3. Duration of geologic processes[a]

Process	Duration (years)
Isostatic recovery from glacial loading	10^3-10^4
Cooling time for a small pluton	10^5
Regional volcanic activity	10^5-10^7
Regional folding or deformation episode	½ 10^7

[a] Data from Ref. 7

in detail here. This volume is a function of the magnitude of the driving force for the process. For example, the effects of a large earthquake will be felt over a larger area than will a small one, and the displacement along a large fault can be much larger than along a small one. Process interactions can be treated mathematically, as in the Geologic Simulation Model,[1] or through analyses of natural systems which are regarded as analogs of repository sites.

The following general comments about the data in Tables 1-3 may be useful.

1. These data do not give expected values for repository sites, because sites should be chosen to avoid known areas of active geologic change.

2. The process rates in Table 1 are estimated ranges of rates and average values for those areas where the processes have been active. Thus, the actual minimum rate for all the processes listed, except possibly crustal plate motion, would be zero. Although values larger than the maximum rates in Table 1 are possible, they are not expected to be significantly larger.

3. Some processes for which rates are given in Table 1 are not assigned recurrence intervals in Table 2 or durations in Table 3. These processes should not, however, be considered constant with time. Rather, they have recurrence intervals and durations which are highly irregular and site-specific, so that generic estimates of these would not be useful.

4. The very long duration of regional deformation episodes in Table 3 means that one can assume constant regional deformation patterns in considering the effects of deformation over time periods less than a million years. This does not mean, however, that such constancy will occur at any specific site within a given region. None of the tables can be used to predict, for example, the birth of a new volcano or fault within a previously inactive area.

5. The estimates of surface process rates in Table 1 tend to be the result of many measurements. However, the estimates of subsurface process rates are based on relatively few measurements, because such processes are difficult to observe and it is difficult to estimate their rates from the geologic record. In a sense, this makes these estimates site-specific rather than generic.

6. The frequency of tectonic events in Table 2 decreases with increasing magnitude. The lifetimes of processes in Table 3 tend to increase with an increase in driving force, as does the extent of the area affected.

The processes and events that are most important in an analysis of the future geologic environment depend on the period of time being considered. This discussion applies to sites that have been chosen for their apparent stability, e.g., those sites where known active fault zones and volcanoes are avoided. For time periods of less than 100 years, the mechanical effects of repository construction and the thermal effects of waste emplacement probably will far outweigh the effects of natural geologic processes. Within 1,000 years, near-surface borehole seals may be disrupted by erosion. By 10,000 years, extensive continental glaciation could occur. Substantial changes in the surface and near-surface environment are likely in glaciated regions, and these changes could alter to a significant extent radionuclide transport between the repository and the biosphere. Glaciation may result in significant changes in the hydrology of the near-surface environment which are difficult to predict and probably will remove any surface markers locating the repository. Loading of the Earth's surface with glacial ice may affect the mechanical stress field at the depth of the repository. For time periods greater than 100,000 years, it is possible that the temperature and pressure fields at the repository site might be significantly different, and the gross chemical and mechanical properties of the host rock could change as a result. In addition, several glacial episodes and unpredictable tectonic and thermal events may occur in this time period. At 1,000,000 years and beyond, it is unwise to speculate on probable changes in the geologic environment.

4. MODELS OF REPOSITORY PERFORMANCE WHICH INCORPORATE GEOLOGIC PROCESSES

4.1 Introduction

Predictions of long-term repository performance can treat the effects of geologic processes using either mathematical or natural analog models. The two methods are not mutually exclusive, but they have different strengths and weaknesses. The advantage of mathematical models is that they provide quantitative results for a well defined set of input data. However, the data selected for a mathematical model will not provide a complete description of an actual site, because the particular processes and their interactions which are incorporated into mathematical models are limited by our understanding of the physical world. On the other hand, natural analog models take into account all physical processes which have created the present physical system regardless of our lack of understanding of the processes. However, the input to a natural analog model is the physical state of the natural site prior to the events or processes being modeled, and it usually is impossible to determine all the parameters needed to describe the initial state of a natural analog. These two methods are complementary, and the uncertainty in applying the results of mathematical models to a repository site is not necessarily more or less than that from applying the results of natural analog models.

Some repository performance-assessment models incorporate the possibility of future changes in the geologic environment. Schwartz and Donath[10] have developed a model of radionuclide transport which incorporates the effects of various types of fault zones. The RHAFE model[11] incorporates time-varying hydrologic sources and boundary conditions in finite-element solutions of the differential equations for groundwater flow. The TERZAGI model[12] solves the differential equations for time-varying hydrologic sources and boundary conditions and includes deformation of the geologic media. The only model we are aware of that attempts a comprehensive simulation of geologic processes over long time periods (i.e., 1,000,000 years) is the Geologic Simulation Model,[1] which was developed at the Pacific Northwest Laboratory. This model is discussed in the following section.

4.2 The Geologic Simulation Model

The Geologic Simulation Model (GSM)[1] is intended to simulate the long-term, far-field effects of geologic processes and events on the groundwater travel time from the repository to the accessible environment at the site of the Basalt Waste Isolation Project (BWIP) in Hanford, Washington. The model does not include radionuclide transport. Because of the large number of events and processes considered and the difficulties in expressing them mathematically, this model is more a bookkeeping system than a computational device.

The events and processes that are incorporated in the GSM are listed in Table 4. The model does not incorporate near-field processes except for shaft-seal failure and repository rupture by faulting. Processes are not treated in great detail, but the level of detail is probably appropriate for a model which treats a time period as long as 1,000,000 years. For example, a single groundwater velocity is calculated with Darcy's law for each whole-rock unit defined in the model. To some extent, the treatment of processes is limited by our basic understanding of the processes themselves. Some processes are treated simply by having the user input the effects. For example, the effect of glacial loading on groundwater hydrology is included by entering the change in hydraulic conductivity that is expected to result from a certain amount of glacial loading. The GSM does not predict either the timing and frequency of events or process rates; these are input to the model as probability functions or polynomial relationships. The model can be run in a Monte Carlo mode to test a range of probabilities. Process interactions are treated by having the processes act sequentially but in a different random order at each time step of the simulation.

The GSM has been written specifically for the BWIP site. The model does not have the capability for handling the deformation of salt or hydrologic flow in fractures. The hydrology of the site being modeled

Table 4. Events accounted for by the Geologic Simulation Model[a]

Submodel	Events and Processes
CLIMATE	Climate index
	Precipitation
	Groundwater recharge
	Orographic effects on precipitation by:
	Uplift of Cascade Range
	Uplift of ranges in model area
CONTINENTAL GLACIATION	Glacial advance/retreat
	Isostatic adjustments
	Displacement of sea
	Glacial erosion/deposition
	Conditions set up for possible major river course change
	Glacier-induced fracturing of basalt
DEFORMATION	Strike-slip or normal faulting
	Thrust or reverse faulting
	Folding
	Changes in hydraulic conductivity
	Changes in hydraulic head
GEOMORPHIC EVENTS	Changes in path length of unconfined aquifer by river movement caused or prevented by:
	Glacial ice
	Flooding by ocean
	River entrenchment into bedrock
	Magmatic event
	Landslide
	Changes in river slope
	Peak river discharge
	River erosion or deposition
	Catastrophic ("Missoula") flooding
HYDROLOGY	Modification of path length
	Modifications in northeast recharge area
	Pressurized recharge by continental glacier
	Modification of head values because of climate
	Calculation of Darcy velocities
	Calculation of travel time
	Checking for repository breach condition
	Permafrost effects

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[a] Ref. 1

Table 4. (Cont'd)

Submodel	Events and Processes
MAGMATIC EVENTS	Direct breaching by magmatic events
	Establishing conditions for possible river course change
METEORITE IMPACT	Change in shaft seal
SEA-LEVEL FLUCTUATIONS	Rise of sea level possibly resulting in:
	Flooding of site
	Sedimentation
	Lowering of groundwater hydraulic gradients
	Changes of river courses
	Lowering of sea level
SHAFT-SEAL FAILURE	Changes in hydraulic conductivity in in shaft seal
SUB-BASALT BASEMENT FAULTING	Changes in hydraulic conductivity
	Time between sub-basalt basement earthquakes
	Fault area of sub-basalt earthquake
	Frequency of sub-basalt earthquake
	Duration of sub-basalt earthquake
	Peak acceleration
	Possible changes in shaft seal
UNDETECTED FEATURES	Starting hydraulic conductivity
	Strike-slip or normal fault
	Thrust or reverse fault
	Folding
	Sub-basalt fault
	Northeast subsystem fault
	Southwest subsystem fault
	Path lengths in unconfined groundwater system

seems to be constrained to the geometry of the BWIP site, but this is not a great deficiency. The model has been written in a clear, modular fashion and is well documented, so that modifications of the model that would be needed for other sites should not be difficult.

The GSM should be useful in predicting the effects of the geologic processes that are included in the model. However, there has been no report of any full use of this model, so it is difficult to evaluate its utility. Of course, it is not possible to validate predictions of the state of the geologic environment 1,000,000 years in the future. One can determine if the results seem reasonable geologically by comparison with the geologic history of the site being modeled and by using a general knowledge of geology, but, of course, these are the same data from which the model was created. The GSM places a large burden on the user in requiring decisions on what probabilities of process occurrence and what process effects are appropriate as input. This makes it difficult to evaluate uncertainties in the predictions of this model. The overall uncertainty would be composed of those due to incomplete or inaccurate definitions of processes and their effects on groundwater flow rates and uncertainties in the functions used to estimate probabilities of the occurrence of different processes. The GSM appears to be useful primarily as a means of testing if any reasonable guesses of a geologic future could result in increased groundwater flow rates.

4.3 Natural Analog Models

A natural analog model of radionuclide transport is one that incorporates only empirical data on transport of naturally occurring radionuclides or stable elements. Natural analog models provide a method that can be used to complement mathematical models for predicting the capabilities of deep geologic repositories for waste isolation. For example, studies of the transport of radionuclides or non-radioactive trace elements from ore deposits and of the processes which form ore deposits can provide valuable information on radionuclide transport and retention in geologic systems.

Uncertainties in natural analog models of repository performance arise largely from differences in the geologic environments of the repository site and the analog and from differences in the initial state of the analog and the present state of the repository site. Uncertainties in predictions of repository performance based on natural analog models can be bounded, but probably not stated precisely or statistically. The range of predictions should be obtained by comparing the rates of processes which have occurred at the analog site with the rates of processes which are likely to occur at the repository site, and then determining what the effects of these processes on radionuclide transport are likely to be.

In a more general sense, the concept of natural analog models forms the basis for the study of geology. Predictions of the future geologic environment are based on geologic history as a natural analog for future geologic processes. The geologic history of a site is determined by comparing its geology with that of other similar sites in order to produce a model of the site which is actually a composite of all the sites studied. One can observe only isolated pieces of any geologic system, so the conceptual model of the whole is developed by drawing inferences from those pieces combined with observations made at other sites. This type of reasoning will be required in any prediction of the effects of future geologic processes at a particular site.

4.4 Effects of Geologic Processes on the Uncertainty in Parameters Used in Radionuclide Transport Models

The action of geologic processes has brought the Earth to its present physical state. Thus, the values of parameters that are needed in repository modeling are the result of the action of geologic processes. The geologic processes which can directly affect the parameters needed in a radionuclide transport calculation are given in Fig. 1. This figure includes only those parameters that are needed in far-field transport modeling. In general, one can say that hydrologic parameters can be affected by surface or subsurface processes, structural parameters by subsurface processes, and chemical parameters

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	PROCESS					
PARAMETER	TECTONICS OR DEFORMATION	THERMAL PROCESSES	EROSION OR DEPOSITION	CLIMATE CHANGE	SEA LEVEL CHANGE	DIAGENESIS
STRUCTURAL						
POROSITY	X	X				X
FRACTURE SIZE OR SPACING	X	X				X
LAYER ORIENTATION	X					
HYDROLOGIC						
HYDRAULIC CONDUCTIVITY	X	X				X
HYDRAULIC HEAD	X		X	X	X	
RECHARGE AND DISCHARGE	X		X	X	X	
PATH LENGTH	X		X	X	X	X
CHEMICAL						
RETARDATION FACTOR		X			X	X

Fig. 1. Geologic processes and the parameters in radionuclide transport models that are affected by them.

by changes in temperature or any process which changes the chemistry of the environment, i.e., by material transport processes. The magnitude of the effect of a particular process on a particular parameter would be dependent on the site being investigated. Whether the action of a process will have either a beneficial or an adverse effect on waste isolation would be site-specific as well.

Figure 1 indicates only the direct relationships between geologic processes and the parameters that are needed in radionuclide transport models. However, any of the geologic processes can effect any physical or chemical parameter through the interactions of the processes themselves. The interactions among geologic processes are indicated in Fig. 2. As with the direct effects indicated in Fig. 1, the magnitude and importance of these indirect effects will depend on the particular site being evaluated. Some process interactions are more direct than others. For example, thermal and tectonic processes are closely related, and sea level changes will directly effect shoreline erosion and deposition. An example of a more subtle interaction is the possible effect of erosion and deposition on the mass distribution of rocks, which can alter the stress field and deformation rates. This type of interaction would be more difficult to model mathematically.

Uncertainties in radionuclide transport parameters due to geologic processes have several sources. First, we do not know the precise effects that the particular geologic processes acting at a given site will have on all the parameters. Second, we do not know what the parameter values and process rates are at present. Finally, we cannot accurately predict future process rates. Numerical estimates of uncertainties in present and past process rates can be obtained from site-specific information. Numerical estimates of uncertainties in future values of model parameters can be obtained from past and present values of process rates and material properties by using mathematical or conceptual models. It must be recognized, however, that estimates of future conditions can be quite subjective and are likely to be little more than educated guesses. Therefore, the validity of numerical uncertainty estimates should always be evaluated in this light.

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CAUSE	EFFECT TECTONICS OR DEFORMATION	 THERMAL PROCESSES	 EROSION OR DEPOSITION	 CLIMATE CHANGE	 SEA LEVEL CHANGE	 DIAGENESIS
TECTONICS OR DEFORMATION		X	X	X		X
THERMAL PROCESSES	X		X	X		X
EROSION OR DEPOSITION	X					X
CLIMATE CHANGE	X		X		X	
SEA LEVEL CHANGE			X			X
DIAGENESIS	X		X			

Fig. 2. Geologic process interactions.

Our conceptual model of radionuclide transport leads us to believe that uncertainties in model parameters due to the effects of future geologic processes should be sufficiently small at a well-chosen site that they will not have a significant effect on predictions of releases of radioactivity to the accessible environment as long as the time period of concern is restricted. It certainly should be possible to select a site which is sufficiently stable that geologic processes will have no significant effect on waste isolation over a period of 10,000 years. Significant geologic changes generally occur over millions rather than tens of thousands of years. Thus, as long as waste isolation is required only for time periods less than a hundred thousand years, future changes in the geologic environment at a stable site should be minor. Of course, it is possible that relatively minor changes, such as small changes in fracture widths, or unanticipated events, such as earthquakes, could significantly decrease groundwater and radionuclide travel times on a local scale. However, such changes would be just as likely to increase travel times as to decrease them. In our opinion, for geologic processes acting at a stable site to result in a significant increase in radionuclide releases to the biosphere would require extremely bad luck in the choice of the site.

It is conceivable that modeling of future geologic changes will not be required as a part of the licensing process for high-level waste repositories, due to the belief that these changes will not affect waste isolation over the time period of concern. A determination of this time period certainly is needed before such decisions are made. It should also be recognized that the determination that a given site is stable is subjective, and that geologists may not agree that a site is sufficiently stable to ensure waste isolation.

5. CONCLUSIONS

Estimates of uncertainties in predicting long-term repository performance due to the effects of geologic processes will require subjective scientific judgments. These uncertainties are best represented by means of bounding values on geologic process rates, their effects on the geologic environment, and the effects of the changing environment on the parameters needed in radionuclide transport modeling. Demonstrating geologic stability at a specific site and over a particular time period will require extensive site investigation and application of geologists' knowledge of geologic conditions at similar sites. Using this information, both mathematical and natural analog models can be used to predict the future geology of the site as it affects waste isolation. The action of geologic processes may either increase or decrease future groundwater travel times. However, at a site chosen for its stability, geologic processes generally act so slowly that they are not expected to perturb the waste isolation system to any significant extent over a period of 10,000 years.

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This report discusses uncertainties in predicting the long-term performance of geologic repositories for high-level waste that result from the effects of future geologic processes. This type of uncertainty arises from uncertainties in determining current rates of geologic processes, predicting process rates over long time periods in the future, and predicting the effects of future geologic processes on repository performance. This report emphasizes the qualitative and judgmental nature of predictions of future geologic processes and their effects on repository performance. However, significant changes generally occur over time periods of 100,000 years or more. Thus, at sites chosen for their stability, geologic processes should not have significant effects on repository performance over a period of 10,000 years.

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