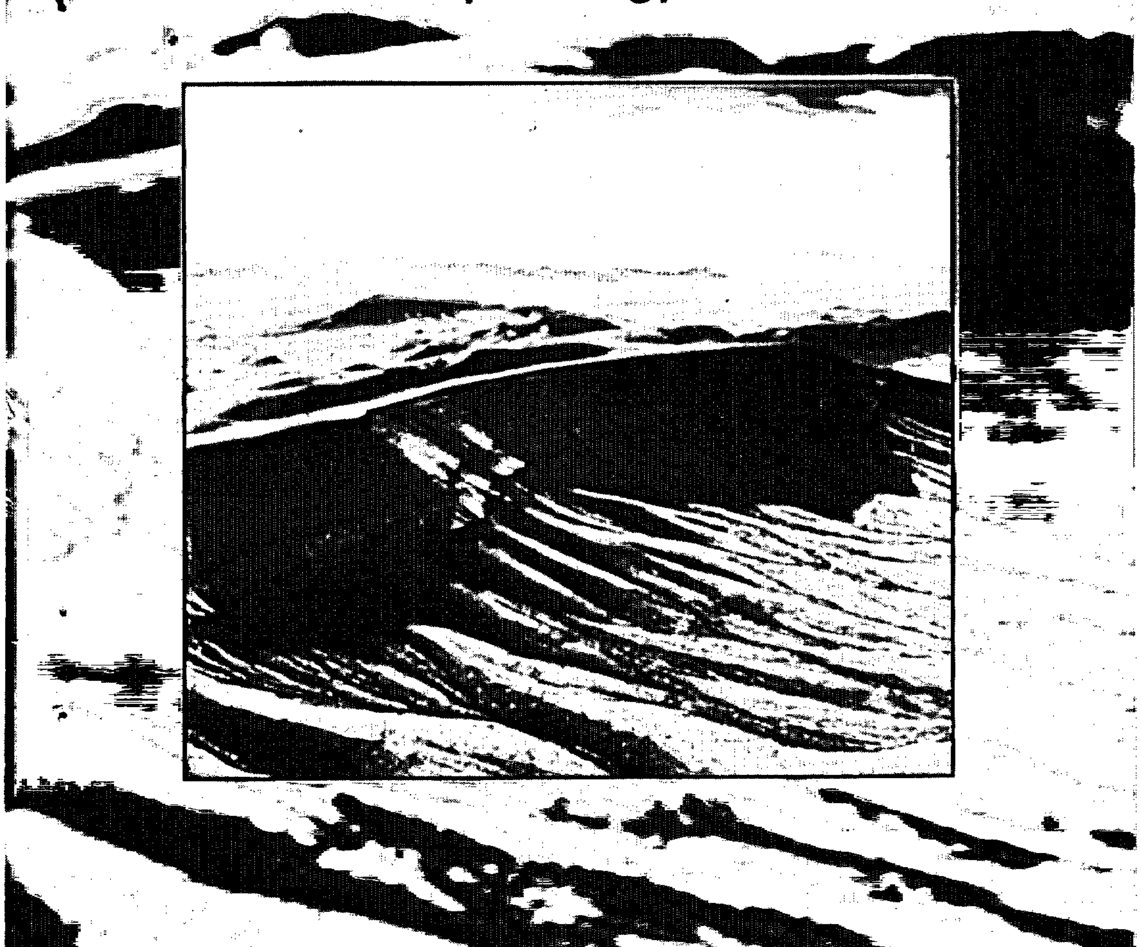
Review of

U.S. Department of Energy Technical Basis Report for Surface Characteristics, Preclosure Hydrology, and Erosion



NATIONAL RESEARCH COUNCIL

Review of

U.S. Department of Energy Technical Basis Report for Surface Characteristics, Preclosure Hydrology, and Erosion

Committee for Yucca Mountain Peer Review:
Surface Characteristics, Preclosure Hydrology, and Erosion

Board on Radioactive Waste Management
Commission on Geosciences, Environment, and Resources
National Research Council

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This report has been reviewed by a group other than the authors according to procedures approved by the Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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PREFACE

The Nuclear Waste Policy Act[1] designates Yucca Mountain, Nevada, as the candidate site for the nation's first permanent geologic repository for spent nuclear fuel and high-level nuclear waste. The act charges the U.S. Department of Energy (DOE) Office of Civilian Radioactive Waste Management (OCRWM) with conducting the necessary studies to determine whether the Yucca Mountain site meets the technical and regulatory requirements for a permanent repository. To meet this responsibility, OCRWM established the Yucca Mountain Site Characterization Office (YMSCO) to conduct the necessary investigations and analyses.

As part of its site characterization effort, YMSCO plans to issue a series of technical basis reports that will summarize and synthesize data, analyses, and interpretations on the following siting-related technical topics:[2]

1. surface characteristics, preclosure hydrology, and erosion;
2. seismicity, tectonics, and volcanism;
3. rock characteristics and geochemistry;
4. preclosure radiological safety;
5. geohydrology and transport; and
6. total system performance assessment.

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1 The Nuclear Waste Policy Act of 1982 (P.L. 97-425) was signed into law in 1983 and amended in 1987 (P.L. 100-203) and 1992 (P.L. 102-486).

2 The Department of Energy is in the process of reorganizing its site characterization program in response to cuts in its FY1996 budget. The committee understands that the DOE may not issue the remaining technical basis reports, but may instead focus on total system performance assessment—which was to be the topic of the sixth and final technical basis report.

These technical basis reports will be used to support regulatory analyses by YMSCO to determine whether the Yucca Mountain site is suitable as a nuclear waste repository.

In late 1994, YMSCO asked the National Research Council to undertake independent, expert peer reviews of these technical basis reports. YMSCO asked the Research Council to analyze the manner in which scientific and technical information was collected, analyzed, and interpreted by DOE and its contractors and, at a minimum, to address the following questions:

- Have the data been collected and analyzed in a technically acceptable manner?
- Do the data, given the associated error and analytical and technical uncertainties, support the technical interpretations and conclusions made within the technical basis reports?
- Are there credible alternative interpretations that would significantly alter the conclusions reached?
- What testing, if any, would discriminate among alternative technical interpretations?
- If such testing is recommended, how effective would it be at reducing significant uncertainties?

YMSCO asked that the review not address regulatory compliance or the suitability of Yucca Mountain as a nuclear waste repository.

The Research Council's Governing Board agreed to undertake these peer reviews in February 1995. The approved statement of task is given in Appendix C. The Governing Board assigned the responsibility for implementing these reviews to the Board on Radioactive Waste Management within the Commission on Geosciences, Environment, and Resources, subject to overall management and control by the Research Council, particularly its Executive Office. Because the technical basis reports will differ substantially in subject and content, the Research Council's Governing Board decided that a different group of experts (committees) would be appointed to review each report. Each expert committee will set forth its review findings and conclusions in a National Research Council report that will be provided to OCRWM and made available to the public without restriction.

The Committee for Yucca Mountain Peer Review: Surface Characteristics, Preclosure Hydrology, and Erosion (see Appendix B) was appointed by the Chair of the National Research Council in June 1995 to review the *Technical Basis Report for Surface Characteristics, Preclosure Hydrology, and Erosion* (DOE Report YMP/TBR-001, Rev. 0, April 1995), referred to as the TBR. The committee held three meetings to gather information and develop its final report (this document), which provides the committee's review and a discussion of its findings and conclusions.

The committee wishes to acknowledge the assistance of several organizations and individuals who made it possible to complete this review on a very compressed time schedule. Jane Summerson (YMSCO) and her staff were very responsive to the committee's many requests for written materials during the course of this review. They also provided organizational and logistical support for the field excursion to Yucca Mountain. Carl Johnson

(Nevada Nuclear Waste Project Office) and his staff made available to the committee numerous documents that were not referenced in the TBR, and they provided advice and logistical support for the field excursion. Mary Ball, Secretary of the town of Beatty, Nevada, graciously opened the town's community center to the committee on a Sunday for a public session during the second meeting. The committee wishes to express its appreciation to all of these individuals for their assistance, and to the other individuals and organizations who provided oral and written input to the committee at its two information-gathering sessions.

CONTENTS

EXECUTIVE SUMMARY

The Committee for Yucca Mountain Peer Review: Surface Characteristics, Preclosure Hydrology, and Erosion was formed by the National Research Council to provide an independent, expert peer review of the U.S. Department of Energy's (DOE's) *Technical Basis Report for Surface Characteristics, Preclosure Hydrology, and Erosion* (DOE Report YMP/TBR-001, Rev. 0, April 1995), referred to as the TBR. The committee addressed its review to the scientific and technical aspects of the TBR as prescribed by its statement of task (Appendix C). The review focused on several issues, including the adequacy of the scientific methodologies employed in data collection, synthesis, and analysis; the validity of data and interpretations; the adequacy of the treatment of uncertainties in describing the current state of understanding; and the effectiveness of the presentation of data, analyses, and interpretations.

The committee based its evaluation of the TBR entirely on scientific judgment. The committee made no attempt to evaluate the science in terms of management decisions related to the suitability of Yucca Mountain as a high-level waste repository. The committee is not properly constituted to make such judgments, and it is specifically prohibited from doing so by the statement of task. The committee attempted to identify weaknesses in data, methodologies, interpretations, and conclusions in the TBR. In some cases, the committee recommended that additional work be done to significantly improve scientific understanding. The committee made no attempt to determine whether the identified weaknesses would have a significant impact on the management decision to site a facility at Yucca Mountain. Nor has the committee determined whether the recommended work would change the management decision to site such a facility. In the committee's view, such judgments are best left to DOE scientist-managers and their oversight bodies. The committee's goal is to help the DOE improve the scientific quality of its TBR.

The primary source of material for the committee's review was the TBR itself and many of the references cited therein. The committee also held two information-gathering meetings to obtain additional information from DOE and other federal agencies, the State of Nevada, and other interested organizations and individuals. These meetings were held in Las Vegas and Beatty, Nevada; the second meeting included a three-day field excursion to Yucca Mountain. Both meetings were open to the public.

The committee's review of the TBR is organized into four chapters. Chapter 1 provides a brief discussion of the purpose and scope of the TBR and an explanation of the procedures used by the committee in its review. Chapter 2 provides the committee's review of the surficial geology and erosion sections of the TBR. Chapter 3 provides the committee's review of the preclosure hydrology sections of the TBR. Chapter 4 addresses the overall effectiveness of the TBR as a synthesis of currently available site characterization data, analyses, and technical interpretations.

The main scientific and technical issues addressed by the TBR are summarized below (in italics) and are followed by the committee's significant conclusions and recommendations. Additional details are provided in Chapters 2 and 3 of this report.

- *Distributions and Relative Ages of Surficial Deposits.* The identification of surficial deposits as presented in the TBR is based on traditional and accepted techniques of analysis. Better age determinations on these surficial deposits are needed, however, in order to estimate erosion rates. Additionally, surficial data from Crater Flat (the drainage to the west of Yucca Mountain), which have been published by State of Nevada scientists, should be referenced, discussed, and integrated into the TBR. The results from surficial mapping need to be integrated better with efforts to evaluate hillslope and stream erosion processes at Yucca Mountain. This integration of mapped surficial units, their ages, and erosion mechanisms should form the basis for evaluation of erosion potential and should be reported in the TBR.

- *Potential for Stream and Debris Flow Erosion.* Fluvial erosion rate estimates reported in the TBR are based on dynamic equilibrium assumptions and may underestimate the fluvial erosion potential of the region. Fluvial erosion rate estimates should be based on bounding calculations, and the possible effects of climate change on fluvial erosion potential should be addressed. The effectiveness of debris flows and landslides as erosive agents of the landscape under current and possible future climatic conditions should also be addressed.

- *Ages of Hillslope Deposits.* The analysis of hillslope ages presented in the TBR is inadequate because it is based on the use of a single geochronological method (cation ratio dating), which is not well understood or calibrated, that is applied to only one type of deposit (heavily varnished hillslope boulder deposits). Different dating techniques (e.g., ^{3}He and ^{10}Be) should be applied to check the cation ratio results, and different types of geomorphic surfaces should be dated by using a variety of techniques in order to obtain estimates of the spatial variability of hillslope ages at Yucca Mountain. The maps of surficial geology referenced in the TBR identified a variety of hillslope units that may have significantly different ages than the heavily varnished hillslope boulder deposits.

- *Long-Term Rates of Erosion.* The analysis of erosion rates presented in the TBR is too narrowly focused on estimating a temporally and spatially averaged rate that can be compared to a regulatory standard. The analysis in the TBR should be expanded to assess the spatial variability of erosion in the region. The TBR should consider the range of erosional processes operating at the site, and identify those portions of the landscape that may be eroding much faster than average. It should also consider the temporal variability of erosion, particularly as it might be affected by climate change.

- *Potential for Surface Flooding of the Proposed Repository.* The application of probable maximum flood (PMF) procedures to estimate flood events as outlined in the TBR is consistent with practices used to design civil structures such as bridges and dams. The values of parameters used in the flood routing calculations (Manning's *n* and the bulking factor), and the assumption of critical flow velocity as the maximum flow velocity at all locations in the channels, provide conservative estimates of flow depths (i.e., overestimates of flow depths). However, the parameter estimates are not supported by data or documentation in the TBR. More work should be done to assess the sensitivity of PMF estimates to these values and assumptions.

- *Potential for Subsurface Flooding of the Proposed Repository.* The discussion of subsurface flooding potential in the TBR is overly brief and devoid of analysis. Two potential sources of subsurface flooding, deep seepage of surface infiltration and rising water tables, are not addressed. Perched water is discussed briefly in the TBR, but its distribution, volume, and age are not adequately discussed or illustrated with graphics. It does not appear to the committee that perched water will pose problems during construction and operation that cannot be handled by reasonably available technology (i.e., technology used in other applications such as mining), but the TBR does not make effective use of existing data to make this point.

- *Availability of a Water Supply in the Yucca Mountain Region for Construction and Operation of the Proposed Repository.* The TBR lacks a clear statement of the technical questions that must be addressed to establish the sufficiency of the water supply for repository construction and operation. The TBR discussion emphasizes historic pumping rates and water level declines predicted by using a numerical model that is based on one conceptual model of the flow system. It provides few data to support technical interpretations and does not consider alternative conceptual models of the ground water system. It is likely that water supply availability can be established by means of bounding calculations, although such a calculation is not provided in the TBR.

OVERALL EFFECTIVENESS OF THE TBR

Chapter 4 of this report addresses the effectiveness of the TBR as a synthesis of currently available data, analyses, and interpretations. In addressing the question of effectiveness, the committee considered the context for the TBR. This TBR is the product of an effort of great national importance: to assess the suitability of Yucca Mountain as a facility for the safe permanent disposal of high-level radioactive waste. For this effort to succeed, the committee believes that DOE will need to demonstrate that it has a good understanding of the scientific and technical issues that would affect the construction and long-term performance of such a facility. Given the importance of this undertaking to the health and safety of present and future generations of this nation's citizens, it is this committee's opinion that the scientific and technical analyses presented in the TBR should meet the highest standards of scientific quality. Considered in this context, it is the committee's judgment that this TBR is not an effective synthesis of data, analyses, and interpretations related to surface characteristics, erosion, and preclosure hydrology.

The concluding chapter of this report provides substantiation for this conclusion and—in the spirit of peer review as a method to improve scientific quality—offers eight recommendations for ways to increase the effectiveness of this and future TBRs. These recommendations are summarized below:

1. The audiences for the TBR should be stated explicitly in the report, and the TBR should be written to be comprehensible by these groups. The designation of target audiences is a DOE policy issue. The committee recommends that DOE policymakers carefully consider the advantages of writing for a broad audience to build scientific credibility and public acceptance for its site characterization program.

2. The TBR should contain a clear statement of the questions to be addressed and hypotheses to be tested for each technical topic. These questions will serve to focus the supporting technical analyses and make it easier for the reader to assess their adequacy.

3. All available scientific and technical information related to the issues addressed in the TBR should be cited and discussed. In addition, essential information (e.g., data, equations, and model parameters) used in analyses should be provided in the TBR, and primary sources should be referenced.

4. The TBR should provide a complete discussion of analyses supporting the technical interpretations; a discussion of alternative hypotheses and the methods used to test them; and a discussion of remaining uncertainties and additional data needed to address them.

5. The TBR should be prepared with the direct involvement of the scientists who did the site characterization studies, and these scientists should be identified in the report. The TBR should also provide a discussion of how data and analyses were selected and integrated.

6. Multiple methods of analysis should be employed in the TBR to improve understanding, reduce uncertainties, and thereby build confidence in the interpretations and conclusions. Bounding calculations are particularly well suited to many of the issues addressed in the TBR and should be applied as part of a multiple-methodology approach to place minimum or maximum bounds on processes and phenomena.

7. The TBR should be illustrated with informative graphics to orient the reader to the region and to illustrate spatial relationships among the various elements of the site. Of particular importance are geologic and topographic maps and cross sections that illustrate the locations of land surfaces, drainages, rock units, surficial deposits, perched and ground water, the proposed repository, and selected data collection sites.

8. Preparation of the TBR should include provision for a rigorous program of peer review by scientists whose work is used in the report. This should occur in addition to external peer review, which serves as an independent check on scientific and technical quality. The peer review process should also include provisions to ensure that the results of internal and external peer review effectively feed back into this and future TBRs and, when appropriate, into the associated scientific and technical programs.

1
INTRODUCTION

The Committee for Yucca Mountain Peer Review: Surface Characteristics, Preclosure Hydrology, and Erosion (Appendix B) was formed by the National Research Council to provide an independent, expert peer review of the U.S. Department of Energy's (DOE's) *Technical Basis Report for Surface Characteristics, Preclosure Hydrology, and Erosion* (DOE Report YMP/TBR-001, Revision 0, April 1995), hereafter referred to as the TBR. This TBR describes and synthesizes scientific data, analyses, and interpretations concerning surface characteristics at Yucca Mountain, Nevada (see Figure 1.1 at the end of this chapter), hydrology relevant to the preclosure phase of the candidate repository, and hillslope and channel erosion. This is the first of a series of planned technical basis reports on Yucca Mountain.[1] These reports will be used by the DOE Yucca Mountain Site Characterization Office (YMSCO) to assess the suitability of the Yucca Mountain site as a permanent repository for the disposal of spent nuclear fuel and high-level nuclear waste.

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[1] The Department of Energy is in the process of reorganizing its site characterization program in response to cuts in its FY1996 budget. The committee understands that the DOE may not issue the remaining technical basis reports, but may instead focus on total system performance assessment—which was to be the topic of the sixth and final technical basis report.

The information in the TBR is organized into four chapters: Chapter 1 provides a brief discussion of the purpose and scope of the TBR and of the geologic setting and history of the Yucca Mountain site. Chapter 2 of the TBR describes the surface characteristics of the site, including drainage characteristics, drainage evolution, and the distribution and ages of surficial deposits. This chapter also assesses the potential for surface flooding that could affect the performance of an underground repository prior to closure. Chapter 3 of the TBR describes the preclosure hydrology[2] of the site. It describes ground water conditions in the unsaturated zone related to the occurrence of perched water. It also assesses the potential for subsurface flooding and the availability of an adequate water supply for repository construction. Chapter 4 of the TBR addresses hillslope and channel erosion at the Yucca Mountain site. It provides descriptions of hillslope evolution and erosion processes. It discusses the Quaternary geochronologic methods that were used to date land surfaces in order to calculate long-term rates of hillslope and channel erosion. Chapter 5 provides a very brief summary of the conclusions in Chapters 2, 3, and 4 of the TBR.

It is important to recognize that the topics addressed by the TBR concern different timescales. Surface flooding and hydrology are considered only during the preclosure phase of the repository, which, as noted in footnote 2, will probably last a few tens of decades. Erosion is considered during the entire period of regula-

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2 The term *preclosure hydrology* as used in the TBR refers to ground water and perched water conditions at the site during repository construction, operation, and closure. The estimated duration of the preclosure phase of the repository is not explicitly stated in the TBR. A 50- to 100-year estimate was provided to the committee during one of its information-gathering sessions.

tory concern for the repository. At present, the U.S. Environmental Protection Agency (USEPA) and U.S. Nuclear Regulatory Commission (USNRC) regulations set this period at 10,000 years. However, the USEPA is in the process of developing health and safety standards for high-level waste disposal at Yucca Mountain. As part of this effort, the National Research Council was asked to provide an analysis of the scientific bases for these standards. An expert committee was formed[3] to provide this assessment; the committee recommended that the health and safety standards should apply to periods of peak risk to the public, which might extend beyond 10,000 years (National Research Council, 1995).

REVIEW CRITERIA

The committee addressed its review to the scientific and technical aspects of the TBR as prescribed by its statement of task (see Appendix C). The committee focused its efforts on assessing the *validity of the data and interpretations* and the *adequacy of the treatment of uncertainties* in describing the current state of understanding. For each of the major topics in the report (i.e., surface characteristics, preclosure hydrology, and erosion), the committee identified the major scientific or technical interpretations and conclusions. The committee examined the quality of the data and methodologies used to support these interpretations and conclusions. The committee also assessed the synthesis of analyses used to support the interpretations and conclusions.

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[3] Committee on Technical Bases for Yucca Mountain Standards.

The committee did not make any judgments about the suitability of the Yucca Mountain site as a nuclear waste repository, nor did it consider regulatory compliance. That is, the committee did not consider whether the site would satisfy the qualifying or disqualifying conditions of Title 10, Part 960 of the Code of Federal Regulations[4] (10 CFR 960). Short discussions of qualifying and disqualifying conditions are given at the beginning of Chapters 2, 3, and 4 in the TBR, but as specified in the task statement, they were not considered by the committee in its review.

The committee relied on its collective expert judgment as informed by conventional scientific usage in applying the "validity" and "adequacy" criteria in the statement of task. The committee applied these criteria as follows:

Validity of Data

- All data used in the analyses should be identified clearly and should be included in the report.
- The data should be collected and analyzed by using generally accepted scientific methods, that is, methods typically employed by other scientists on problems of a similar nature.
- Data collection and analysis methodologies should be explained clearly.

[4] Title 10, Part 960 of the Code of Federal Regulations, General Guidelines for the Recommendation of Sites for Nuclear Waste Repositories.

Validity of Interpretations and Conclusions

- The interpretations and conclusions should be stated clearly in the report.
- The interpretations and conclusions should be supported by available data.
- The interpretations and conclusions should be based on generally accepted methods of data analysis.
- All available relevant and technically acceptable data, including data collected by workers not associated with the site characterization program, should be considered explicitly in the analyses.
- All assumptions in the analyses should be stated clearly.
- All plausible alternative conclusions and findings should be considered against available data.

Adequacy in the Treatment of Uncertainties

- Uncertainties in the methodologies, data, findings, and conclusions should be identified clearly and discussed.
- The need for additional data collection to reduce uncertainties should be discussed.

These review criteria subsume questions a-d in the statement of task (Appendix C).

The statement of task gives the committee flexibility to apply other criteria in its review of this TBR (see Appendix C). The committee decided also to assess the quality of presentation of the TBR and the process for preparing it. The criteria that the committee applied in these aspects of its review are given below:

Presentation

- The data, analyses, and conclusions and findings should be presented in a clear and concise manner.
- The graphics should be informative and adequate to illustrate and support the interpretations and conclusions.

Report Preparation

- The TBR should be prepared with the direct involvement of scientists whose data and conclusions are used in the report.
- The science in the TBR should be peer reviewed by the scientists whose data and conclusions are used in the report.

REVIEW BASIS

The committee wishes to emphasize to the reader, and particularly to DOE managers, that its evaluation of the statement of task questions related to alternative interpretations, testing, and uncertainty reduction (i.e., questions c-e in Appendix C) is based entirely on scientific judgment. The committee made no attempt to evaluate these questions in terms of DOE management decisions related to the suitability of Yucca Mountain as a high-level waste repository. The committee is not properly constituted to make such judgments, and it is specifically prohibited from doing so by the statement of task. The committee recognizes, however, that the reduction of scientific uncertainty to very low levels is difficult and could require lengthy study. The committee believes that DOE scientist-managers and oversight bodies must ultimately judge how much scientific data is needed to make sound and effective policy decisions regarding the Yucca Mountain site.

The committee attempted to identify weaknesses in data, methodologies, interpretations, and conclusions in the TBR. In some cases, the committee recommended that additional work be done to significantly improve scientific understanding, and—equally as important—the scientific credibility of the site characterization program. The committee made no attempt to determine whether the identified weaknesses would have a significant impact on the management decision to site a facility at Yucca Mountain. Nor has the committee determined whether the recommended work would change the management decision to site such a facility. In the committee's view, such judgments are best left to DOE scientist-managers and appropriate oversight bodies.

SOURCES OF INFORMATION USED IN REVIEW

The primary source of materials for the committee's review was the TBR itself and many of the supporting materials referenced in Appendix A of the TBR. The committee requested, and DOE provided, multiple copies of all of the materials cited in Appendix A of the TBR. The committee consulted these materials frequently during the course of its review.

The committee also held two information-gathering meetings to obtain additional information about the report from DOE and other federal agencies, the State of Nevada, and other interested organizations and individuals. Both meetings were open to the public. At the request of the committee, the YMSCO distributed advance copies of meeting notices to the organizations and individuals it had identified as "stakeholders" in the site characterization process.

Prior to its first meeting, the committee asked federal, state, and local government agencies and organizations with an interest in Yucca Mountain to designate formal liaisons to the committee. A list of liaisons is given in Appendix D. These liaisons were invited to provide the committee with information they deemed relevant to its review of the TBR, either orally at the information-gathering meetings or in writing. In return, these liaisons were provided with lists of documents received by the committee, advance copies of meeting agendas, and copies of minutes of open meetings, to keep them fully informed concerning the committee's work.

The committee's first information-gathering meeting was held on July 19-20, 1995, in Las Vegas, Nevada. At this meeting, the committee received formal presentations and written materials from several liaisons. The committee also obtained comments from liaisons and other members of the public in public comment sessions scheduled during each day of the meeting. The agenda for this meeting and the list of speakers can be found in Appendix E.

The committee's second information-gathering meeting was held on August 27-29, 1995, and was organized around a three-day field excursion to Yucca Mountain. The committee also held a half-day meeting at the Community Center in Beatty, Nevada, on

August 27, 1995, where it questioned scientists on the topics of perched water, water supply, and probable maximum flooding. The public was also given an opportunity to provide comments and information at this session. A copy of the agenda for this meeting appears in Appendix E.

The purpose of the field excursion was to examine evidence in the field and to discuss data, analyses, and conclusions in the TBR with scientists who are working at the Yucca Mountain site. The excursion was organized by the committee with the assistance of staff from YMSCO and the Nevada Nuclear Waste Project Office. Field trip stops were selected by committee members to address their specific questions and concerns about the interpretations and conclusions in the TBR. At the committee's request, YMSCO and the Nevada Nuclear Waste Project Office designated scientists to make brief presentations or respond to the committee's questions at each stop. An agenda for the field excursion also appears in Appendix E, and the locations of the field trip stops are shown in Figures 1.1 and 1.2.

The committee found the open sessions and the field excursion to be very helpful in its review of this TBR. These sessions helped the committee to understand the process used by YMSCO to produce the TBR and also provided the committee with additional relevant scientific and technical information that was not referenced in the TBR. Some of this additional material was published after the release of the TBR. Other material was available prior to release of the TBR, but presumably was not deemed to be of direct relevance by those responsible for preparing the report. Although the TBR was reviewed on its own merits, this additional information was helpful to the committee in clarifying its thinking about the need for additional work and analyses. The committee did attempt to identify and obtain all materials deemed relevant to its review. The review of the literature, however, was not exhaustive, due mainly to limitations of time. Additionally, there may be relevant literature that the committee was unable to identify or obtain.

The exchanges that occurred during the open meetings and field excursion among the scientists who work for the many organizations concerned with Yucca Mountain were also very helpful to the committee in its review. These exchanges helped the committee to understand points of disagreement among scientists working in the Yucca Mountain area and the nature of uncertainties in the data, analyses, interpretations, and conclusions presented in the TBR. These exchanges also provided the committee with an enlightening view of science management at Yucca Mountain.

The committee held three executive sessions during the course of its review of this TBR. Executive sessions were held after the two information-gathering meetings (discussed above), and a third executive session was held at the National Academy of Sciences' Beckman Center in Irvine, California, in October 1995. Executive sessions were held to conduct the following business: (1) the conflict-of-interest discussion, which is required by the National Research Council of all committees; (2) discussion of the statement of task; (3) discussion of information provided during the open sessions; (4) development of recommendations; and (5) drafting of the report. Following established practices of the Board on Radioactive Waste Management, the parent board to this committee, these executive sessions were closed to all but National Research Council committee and staff members. Although the minutes of these executive sessions were not distributed to the sponsor, liaisons, or other members of the public, the minutes of all other sessions were made public.

ORGANIZATION OF THIS REPORT

The committee's detailed review of Chapters 2, 3, and 4 of the TBR is provided in Chapters 2 and 3 of this report.[5] The committee's review of surficial characteristics and erosion is presented in Chapter 2 of this report. The review of preclosure hydrology is presented in Chapter 3. Chapter 4 of this report provides some general observations about the TBR and the processes used to produce it. This chapter also offers some constructive suggestions for improvements.

This report is organized to group related topics and differs somewhat from the organization of the TBR. Table 1.1 provides a roadmap between the sections of the TBR and the review of those sections in this report. The committee chose this alternative organization scheme to reduce redundancy in its review, to provide better flow to the text, and to allow for a more logical development of ideas.

Each major section in Chapters 2 and 3 of this review (indicated in the left-hand column in Table 1.1) is structured to provide an explicit discussion of each of the questions in the statement of task (Appendix C). The headings for these subsections and the corresponding statement-of-task questions (in italics) are shown below:

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[5] Chapters 1 and 5 of the TBR contain background and summary materials only. They were read but not reviewed by the committee.

TABLE 1.1 Organization of the Review of the TBR

Section of This Report	Section in the TBR
Chapter 1: Introduction	—
Chapter 2: Surface Characteristics and Erosion Potential	2.1
Review of Surficial Geology	2.2, 2.3, 2.4
Review of Erosion Potential of Alluvial Deposits	2.3, 2.4, 2.5, 4.4.3
Review of Quaternary Geochronology	4.3
Review of Erosion Rates	4.1, 4.2, 4.4, 4.6,[a] 4.7
Chapter 3: Preclosure Hydrology	3.1
Review of Surface Flooding	2.6
Review of Subsurface Flooding	3.2[b]
Review of Water Resource Potential	3.3
Chapter 4: Concluding Comments	—

[a] The TBR has no Section 4.5.

[b] Page 3-5 is miscollated, separating two parts of Section 3.2.2.

- Adequacy of Data Collection and Analysis. *Have the data been collected and analyzed in a technically acceptable manner?*
- Support for Technical Interpretations. *Do the data, given the associated error and analytical and technical uncertainties, support the technical interpretations and conclusions made within the technical basis report?*

- Credible Alternative Interpretations. *Are there credible alternative interpretations that would significantly alter the conclusions reached?*

- Testing to Discriminate Among Alternative Interpretations. *What testing, if any, would discriminate among alternative technical interpretations? If such testing is recommended, how effective would it be at reducing significant uncertainties?*

To aid the reader of this review, the committee has produced several figures for this report from materials obtained from DOE and its contractors. These figures are collated for the reader's convenience in this introductory chapter. Figure 1.1, which is modified from Figure 1.3-2 in the TBR, is a location map for the Yucca Mountain area showing major features and the locations of the field trip stops. Figure 1.2, which is modified from Figure 2.3-1 of the TBR, shows topography of Yucca Mountain and the location of the North Portal Site, South Portal Site, Shaft Site No. 2, and a few field trip stops. Figures 1.3 and 1.4 are north-south and east-west cross sections, respectively, through Yucca Mountain. They show elevations, the location of the proposed repository, geology and structure, the position of the water table, and locations of selected wells.

The committee has provided references as needed throughout this report to support the discussions and conclusions of its review. In certain parts of the review, it is useful for the reader to know which of the references were cited in the TBR and which are from other sources. In order to make this distinction clear, the committee has adopted the convention of boldfacing all of the references cited in the TBR.

The committee recognizes that there is likely to be broad interest in this review of the TBR. Therefore, the committee has endeavored to write its report to be understandable to the educated lay person. The committee has avoided the use of unnecessary jargon and has used footnotes throughout this report to define specialized terms and explain complicated principles. It has also provided a list of acronyms and symbols in Appendix A.

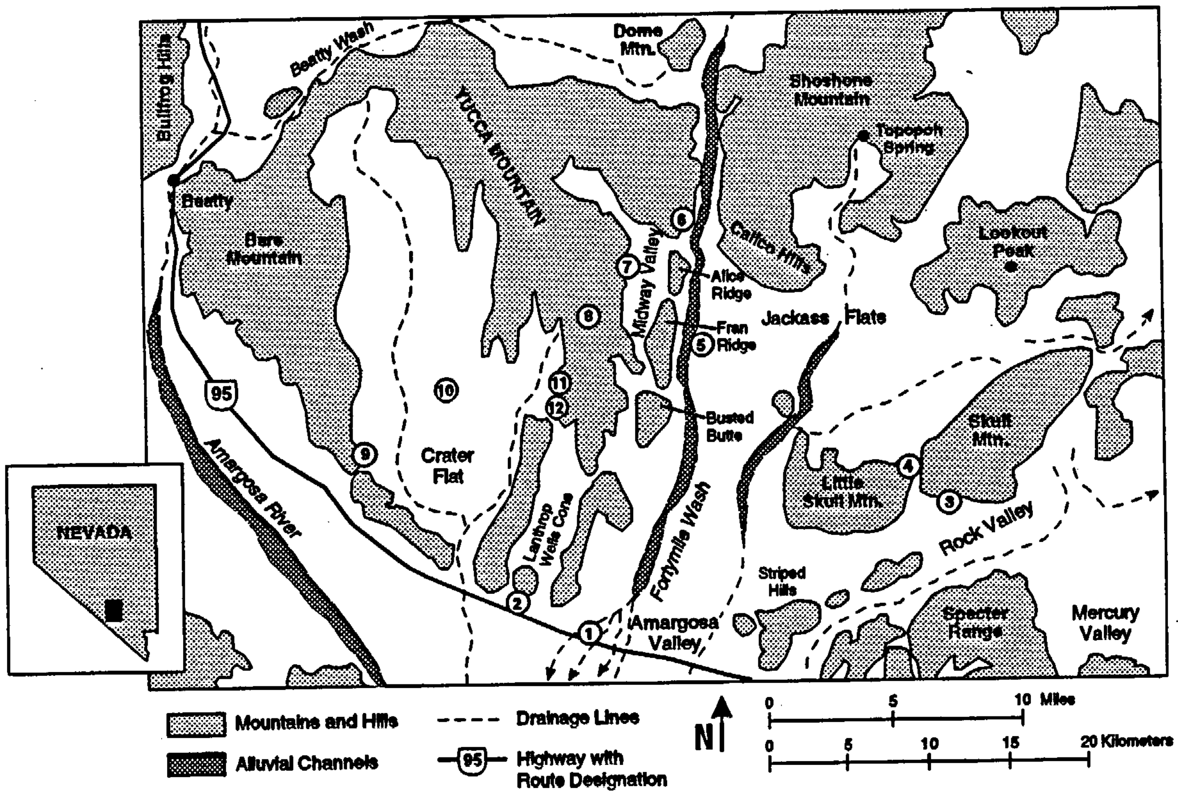


FIGURE 1.1 Generalized location map of the Yucca Mountain, Nevada, region (after TBR Figure 1.3-2). The numbered circles indicate the locations of the field trip stops. The numbers are keyed to the field trip agenda in Appendix E.

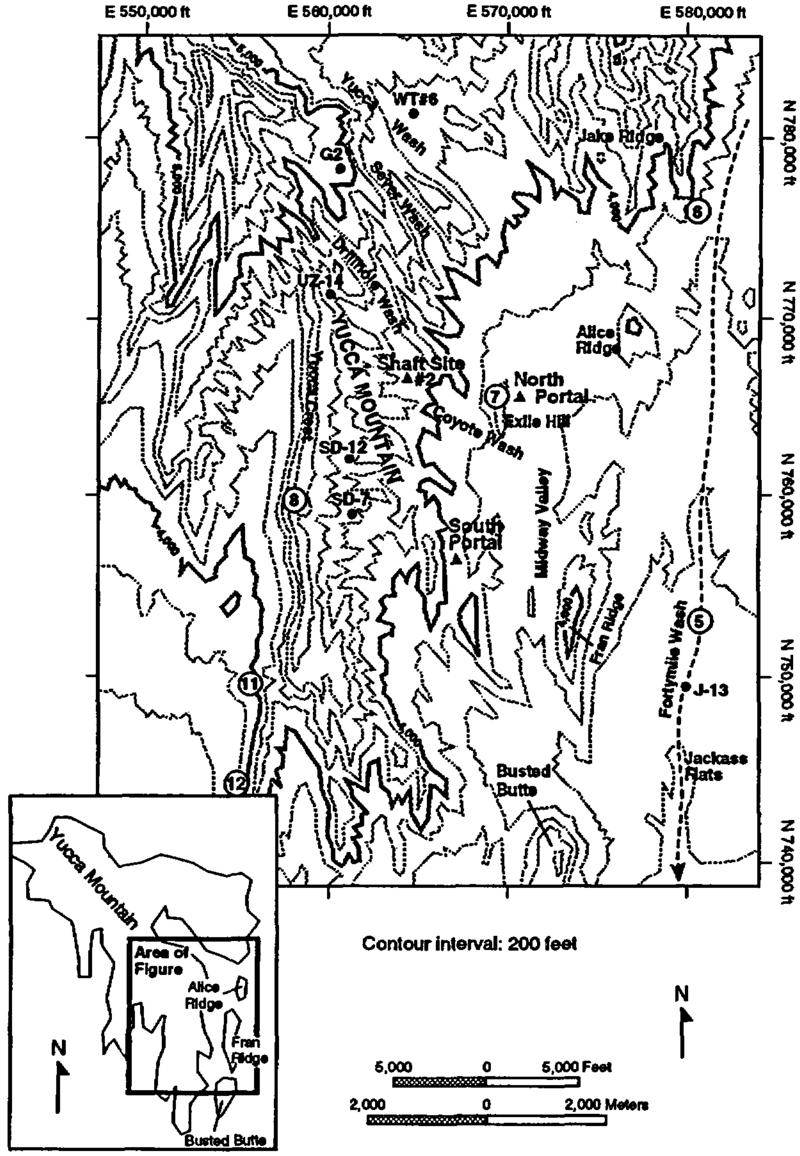
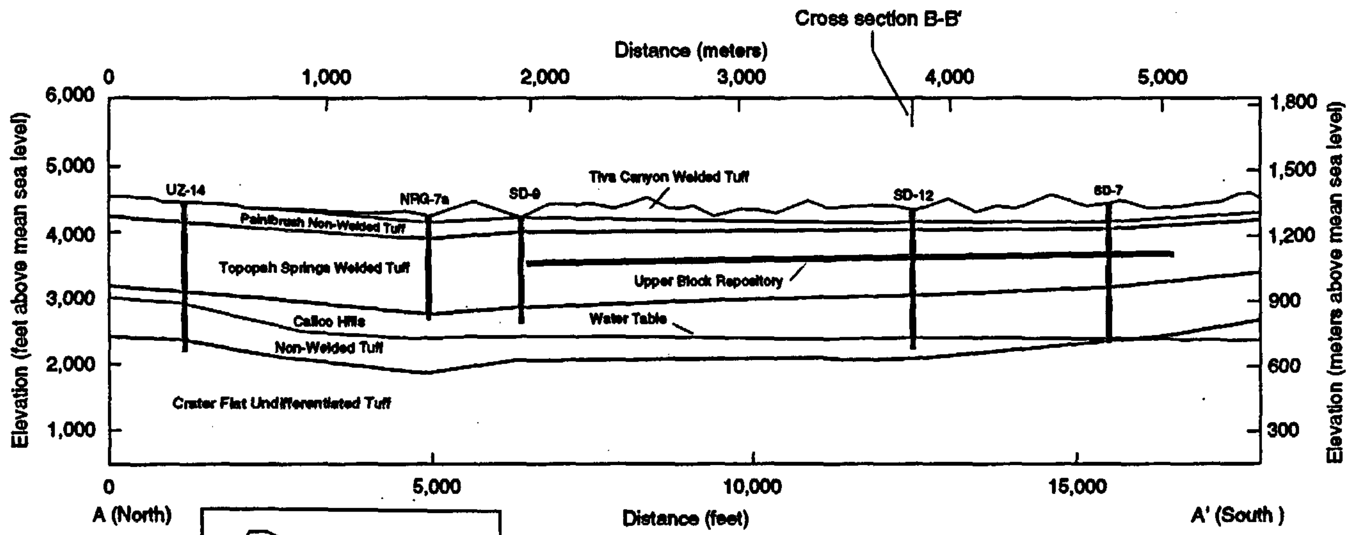
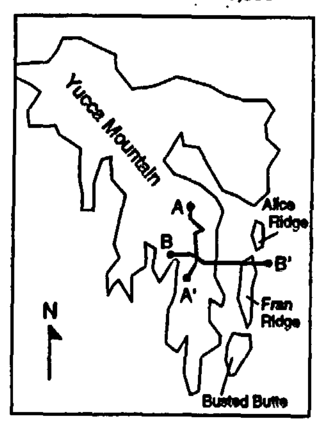


FIGURE 1.2 Topography of Yucca Mountain and vicinity, showing the locations of the North Portal Site, South Portal Site, Shaft Site No. 2, and selected drillhole locations (after TBR Figure 2.3-1). The numbered circles indicate the locations of the field trip stops (see Appendix E). The Fortymile Wash Drainage Basin, which is partially shown in the figure, includes Yucca Wash, Sever Wash, Drillhole Wash, and Coyote Wash. The approximate position of Fortymile Wash is indicated by the dashed line.





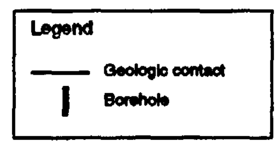
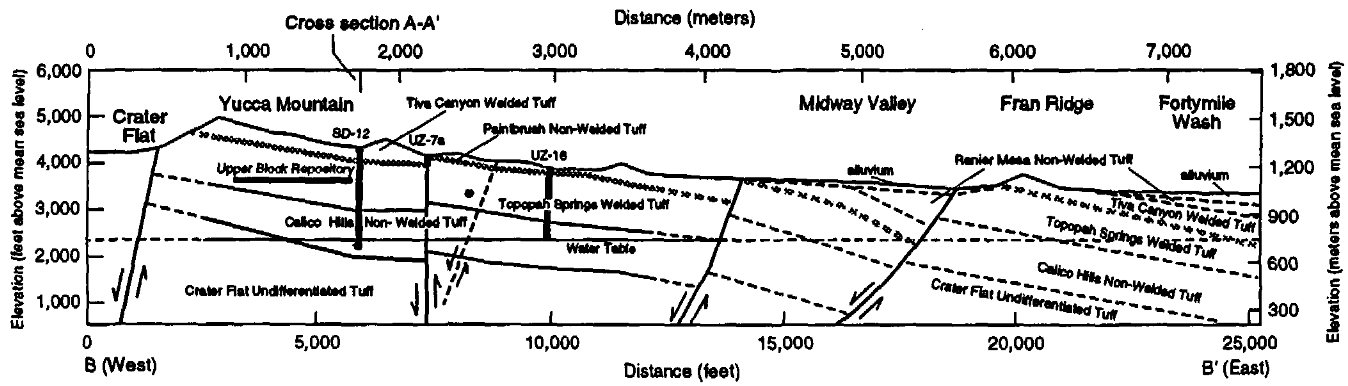
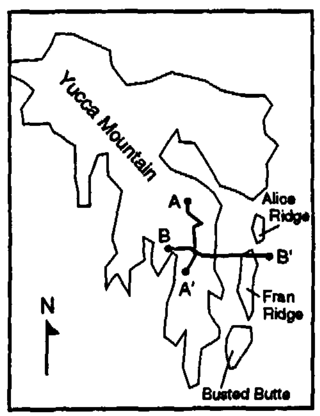


FIGURE 1.3 North-south cross section (A-A') through Yucca Mountain showing the elevation of the land surface, geologic units, major faults, and selected wells. The location of the proposed repository is projected onto the cross section. The figure is based on materials received from the DOE and its contractors during the committee's information-gathering sessions.





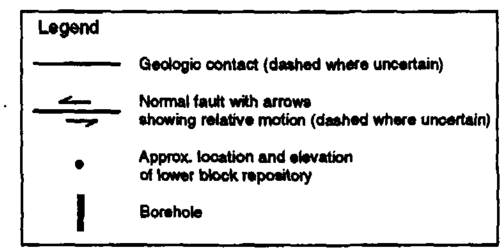


FIGURE 1.4 East-west (B'-B) cross section through Yucca Mountain showing the elevation of the land surface, geologic units, major faults, selected wells, and the location of the proposed repository. The figure is based on materials received from the DOE and its contractors during the committee's information-gathering sessions.

2
SURFACE CHARACTERISTICS AND EROSION POTENTIAL

This chapter provides a review of the technical basis report (TBR) sections related to surficial geology; stream (alluvial) deposits and the potential for stream erosion; and the ages, stability, and erosion of hillslope deposits at Yucca Mountain. Discussions of these issues appear in several different sections of the TBR, as noted in Table 1.1 of this report. The committee has chosen to group and discuss these topics in a single chapter, so that the surficial geology of the site—the product of erosion—can be related directly to erosion rates and processes.

REVIEW OF SURFICIAL GEOLOGY

Sections 2.1 to 2.4 of the TBR discuss the surficial geology of the Yucca Mountain site. The focus of this discussion is on the distribution and relative ages of surficial deposits at the site. A later section of the chapter reviews the erosion potential of these deposits.

Adequacy of Data Collection and Analysis

The TBR presents information on the distribution and ages of surficial deposits and the potential for hillslope and stream (fluvial) erosion, with an emphasis on the Fortymile Wash drainage basin (Figures 1.1 and 1.2). Various geological maps constructed for the Yucca Mountain region identify surficial deposits (**Frizzell and Shulters, 1990**;[1] **Wesling et al., 1992**; Faulds et al., 1994; **Lundstrom et al., 1995**[2]). The TBR makes reference to some of these maps but does not reproduce any of them. Although a variety of surficial deposits are identified, the TBR addresses the age and stability of only two types of deposits: alluvial deposits and coarse (boulder) hillslope deposits.

Maps published by Department of Energy (DOE) scientists and collaborators primarily cover the eastern side of Yucca Mountain (**Wesling et al., 1992**; **Lundstrom et al., 1995**). Maps published by the State of Nevada cover the western side of Yucca Mountain (Faulds et al., 1994). Identification of surficial geologic units on these maps is based on the following criteria: landform morphology, relative geomorphic position, relative degree of preservation of surface morphology, relative soil development, characteristics of vegetation on the geomorphic surfaces, and drainage network patterns (**Wesling et al., 1992**; Faulds et al., 1994; **Lundstrom et al., 1995**). The procedures used to define map units are consistent with practices used by most scientists for surface mapping.

The map constructed by **Lundstrom et al. (1995)** for the eastern side of Yucca Mountain is largely compatible with the map

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1 References cited in the TBR are denoted by boldface type throughout this report.

2 Listed as *in press* in the TBR.

published by the state of Nevada for the western side of Yucca Mountain (Faulds et al., 1994). Differences between mapped units appear to be relatively minor and are due to differences in interpretation of some of the surfaces owing to relatively poor age control.

The production of a surficial geological map requires that both the spatial distribution of mappable units and their ages be determined. The ages of most of the mapped surficial deposits at Yucca Mountain are not known. As noted previously, research reported in the TBR focuses on dating two types of deposits, alluvial and hillslope deposits. The ages of the hillslope deposits were estimated with cation ratio techniques. A review of this work is presented later in this chapter. The alluvial deposits have been dated by using radiocarbon techniques, U-trend techniques, and soil characteristics (Taylor, 1986; Hoover, 1989). More recent age determinations employ thermoluminescence, tephrochronology, and U-series disequilibrium techniques. These recent data are not included in the TBR but were presented to the committee during the field excursion. These recent determinations provide age estimates of 40-100 ka[3] for the youngest terrace deposit adjacent to Fortymile Wash (S.C. Lundstrom, U.S. Geological Survey, personal communication). These estimates are considerably younger than the 150-ka estimate of this same terrace presented in Section 4.4.3.1 of the TBR. This difference is significant because it affects the assessment of the potential for fluvial erosion at the Yucca Mountain site.

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[3] The unit ka denotes thousands of years before the present, where the "present" is defined relative to some reference year, usually A.D. 1950 for radiocarbon dates.

Ages of other types of hillslope deposits were determined as part of a research program designed to evaluate recent faulting (Paces et al., 1994). Trenches were dug across faults near the bases of certain hillslopes, and colluvial deposits exposed in the trenches were dated by using U-series disequilibrium methods on pedogenic carbonates and thermoluminescence techniques on quartz grains. Surface ages at these sites range from modern to approximately 100 ka (Paces et al., 1994). These ages suggest that the colluvial deposits at trench locations near hillslope bases are extremely stable. However, the TBR does not report these data.

Support for Technical Interpretations

The ages of the surficial units reported in the TBR are not well determined, which makes it difficult to assess the validity of the interpretations. The committee views surficial mapping as a first step in a determination of the potential for landscape change at the site. Other components of this analysis should include (1) an identification of the major geomorphic processes that are responsible for these mapped geomorphic surfaces and deposits, including possible interactions between hillslope and channel erosion processes, and (2) the ages of these surficial deposits.

Credible Alternative Interpretations

As noted previously, there are differences in the interpretation of mapped units between Lundstrom et al. (1995) and Faulds et al. (1994). The TBR should have cited the Faulds et al. (1994) map and discussed these differences.

The TBR emphasizes the east side of Yucca Mountain in both the surficial mapping and the evaluation of fluvial erosion (next section). It does not give the rationale for this emphasis, but presumably DOE scientists reason that erosion potential is higher on this side of Yucca Mountain. An alternate hypothesis would be that there is also a significant potential for erosion of Yucca Mountain from the western drainages (i.e., the Amargosa River drainage) and hillslopes. As shown in Figure 1.4, the western side of Yucca Mountain is significantly steeper than the eastern side and therefore may be more prone to erosion. Is erosion of this slope likely under present or future climate conditions? Note that such erosion could occur by either scarp retreat or stream head-cutting. What would the effects of climate change be on erosion of the western slope during the period of regulatory concern? Surficial investigations on the western side of Yucca Mountain could provide the information needed to evaluate these questions.

Testing to Discriminate Among Alternative Interpretations

Comparison of surficial units and their ages on both the east and the west sides of Yucca Mountain is needed to evaluate the results of DOE and State of Nevada mapping programs and to compare landforms and geomorphic processes. Better age determinations are needed on the mapped units on both sides of Yucca Mountain. Such ages would significantly reduce scientific uncertainties in hillslope and fluvial erosion histories.

Summary and Conclusions

The geomorphic surfaces and deposits at Yucca Mountain are of different ages and likely were formed by a variety of geomorphic processes. The identification of surficial units is a starting point in any exercise to determine the processes by which these geomorphic surfaces have formed, their ages, and their relative stability. Such data are important for assessing long-term erosion potential, because they attest to the spatial and temporal rates of erosional processes operating in the region.

Based on information received by the committee during the field excursion, surficial mapping appears to be a relatively recent effort at the site, and it does not appear to be well coordinated with efforts to evaluate hillslope and stream erosion processes. The committee believes that the coordination of this work would significantly improve scientific understanding of erosion processes at the site and the effectiveness of the TBR in conveying this understanding.

REVIEW OF EROSION POTENTIAL OF ALLUVIAL DEPOSITS

Sections 2.3-2.5 and 4.4.3 of the TBR discuss alluvial deposits and their erosion potential. The focus of that discussion is on the following two issues:

1. What is the thickness of alluvium in the major stream valleys at Yucca Mountain?
2. What is the potential for stream and debris flow erosion at the site?

Adequacy of Data Collection and Analysis

This review of the adequacy of data collection and analysis focuses on three aspects of the discussion in the TBR: (1) thicknesses and ages of alluvial deposits; (2) surface drainage, fluvial erosion, and Fortymile Wash evolution; and (3) debris flow deposits and debris flow potential. These topics are treated sequentially in the following sections.

Thicknesses and Ages of Alluvial Deposits

In Sections 2.3 and 4.4.3, respectively, the TBR provides data on the thicknesses and ages of alluvial deposits. It also presents interpretations of alluvial history and potential for erosion based largely on these data. The discussion of alluvial deposits focuses on Fortymile Wash and adjacent drainages (Figure 1.1); there is no discussion of alluvial deposits on the west side of Yucca Mountain. An implicit assumption was made in the TBR that Fortymile Wash is of greatest concern in terms of the erosion potential of Yucca Mountain. A rationale for this assumption is not given in the TBR, but the committee speculates that it is based on the following site characteristics: Alluvial deposits on the east side of Yucca Mountain are extensive, and the North Portal (Figure 1.2) is immediately adjacent to these deposits. The elevation of the upper block of the proposed repository is between about 3,450 and 3,650 feet (1,052-1,113 m)[4] above mean sea

[4] The committee estimated the elevation of the proposed repository using Figure 4.1.1-1 of the TBR and a topographic map of the region. The elevation of the upper block of the proposed repository dips slightly toward the north. Its elevation is about 3,650 feet (1,113 m) at the south end and about 3,450 feet (1,052 m) at the north end.

level, which is above the alluvium-bedrock contact in Fortymile Wash (e.g., Figure 2.1).

Data on the thicknesses of alluvial deposits were derived from analysis of sediments from drillholes. The locations of the drillholes are shown in Figure 2.3-1 of the TBR. The TBR does not present these data effectively (i.e., the data are listed in the text but not tabulated or analyzed) or evaluate variations in depth of alluvium in various parts of the stream network and the relationship of alluvium to the underlying bedrock surface. Consequently, the committee had difficulty in reviewing these data, particularly with respect to spatial variations in sediment thicknesses in the valleys east and south of Yucca Mountain.

Stream profiles showing the thicknesses of alluvial deposits and depth to bedrock along Fortymile Wash were presented to the committee on the field excursion (Figure 2.1). The TBR should have included such profiles for all significant drainages. The data presented in the TBR provide a general picture of thicker accumulations of alluvium in Fortymile Wash than in the smaller tributaries. Figure 2.1 shows that the alluvial fill in Fortymile Wash thickens significantly in the downstream direction.

Section 2.4.1 of the TBR describes the alluvial deposits of Sever Wash and Midway Valley near the North Portal Site (see Figure 1.2). Sever Wash is described as an area characterized by alluvial fan aggradation and minor erosion in contrast to the area west of Midway Valley, where narrow, steep-sided valleys are

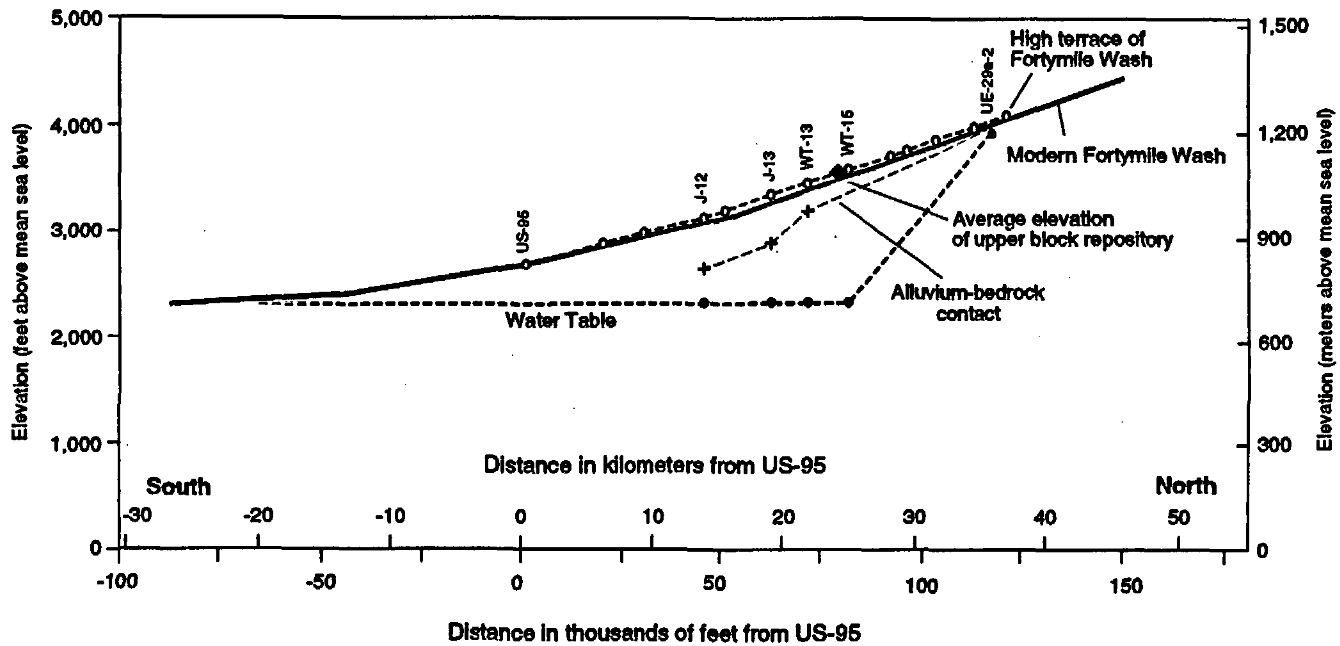

FIGURE 2.1 Longitudinal profile of Fortymile Wash (from S.C. Lundstrom, U.S. Geological Survey, distributed to the committee during the field excursion). The approximate location and elevation of the proposed upper block repository with respect to Fortymile Wash is projected onto the cross section for comparison purposes.

incised into bedrock. The TBR does not provide any data or discussion to support the hypothesis that Sever Wash is currently an area of minor erosion.

There appears to be an implicit assumption made in the TBR that current erosional and depositional trends can be extrapolated into the future. That is, the TBR assumes that sites of current alluvial deposition have low potential for future erosion, whereas sites currently eroded to bedrock have greater potential for future erosion. This apparent assumption ignores temporal patterns of erosion and sedimentation common to semiarid and arid regions (e.g., Schumm, 1977; Wolman and Gerson, 1978). Erosion rates may decrease after channels are eroded to competent bedrock. Thick sequences of alluvial fill represent material that can be eroded easily under the proper hydrologic conditions. Such conditions might occur, for example, with a change in climate.

Surface Drainage, Fluvial Erosion, and Fortymile Wash Evolution

Fortymile Wash in the vicinity of Yucca Mountain is dry except during runoff-generating storm events. Continuous streamflow from Fortymile Wash into the Amargosa River (Figure 1.1) and extensive streamflow within the Fortymile Wash drainage system occurred during the 1969 and 1995 flood events (Beck and Glancy, 1995). Bank erosion and sediment deposition occurred during these events as well (Beck and Glancy, 1995). Fortymile Wash has been gauged since 1969, which is not a sufficient time interval to evaluate flood magnitude and frequency and associated erosion potential. (Chapter 3 of this report discusses the magnitudes of flood events that have occurred at Yucca Mountain.) The

TBR does not address the possible effects of climate changes that may alter the rainfall-runoff regime and thereby affect the stability of alluvial deposits in Fortymile Wash.

Sections 2.5.1 and 4.4.3 of the TBR address the potential for stream erosion in Fortymile Wash and its tributaries. Section 2.5.1 presents the early history of the evolution of Fortymile Wash. It describes the present channel as being in dynamic equilibrium, with neither net aggradation nor net erosion occurring within the system (Huber, 1988). Data that support this hypothesis of dynamic equilibrium are not presented, nor is there a discussion of whether such dynamic equilibrium would be maintained under reasonable scenarios of climate change over the period of regulatory concern.[5]

Debris Flow Deposits and Debris Flow Potential

Surficial mapping by Swadley et al. (1984) and by Lundstrom et al. (1995) identifies a few debris flow deposits at Yucca Mountain. Colluvium that could have been transported by debris flows is noted to underlie the North Portal Pad (Figure 1.2). The TBR does not discuss the ages of these deposits and the potential for future debris flows at this location. The TBR does note that debris flows have occurred within recent years at Yucca Mountain. Although it considers debris flows as relatively unimportant agents of erosion under the current climate regime, the

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[5] The concept of *dynamic equilibrium* as applied to rivers in arid and semiarid systems is not well defined, as noted elsewhere in the text. The committee takes the term *dynamic equilibrium* to describe the condition of a river channel that is adjusted to its water and sediment loads such that no net aggradation or degradation occurs over periods of decades to centuries.

TBR presents no data to support this interpretation. The TBR also does not address the potential for landsliding in the region.

Support for Technical Interpretations

The TBR presents several conclusions concerning alluvial deposits, debris flows, and the potential for erosion: (1) streams are in dynamic equilibrium; (2) the potential for erosion of the alluvial fills is low; (3) rainfall rates and intensities are too low to accomplish significant fluvial erosion under current climatic conditions; and (4) debris flows are minor erosive agents on the landscape. As noted in the previous discussion, however, the TBR does not present data or analyses to support these interpretations.

The assumption of dynamic equilibrium is not well documented in the report and probably should not have been made for the evaluation of fluvial erosion potential. As noted previously, determination of the ages of the alluvial fills is work in progress, and these ages are poorly established at present. The TBR does not define the relationships among rainfall events, runoff production, and channel erosion. Consequently, erosion processes cannot be evaluated based on the data in the TBR for current or reasonable future climatic conditions.

Credible Alternative Interpretations

There are several alternative interpretations or hypotheses that should be addressed in the TBR. These include the following:

1. Stream channels in Fortymile Wash are not in dynamic equilibrium. The concept of dynamic equilibrium is not well de-

fined for semiarid channel systems. Research on the alluvial history of stream channels in semiarid regions indicates that they experience multiple episodes of scour and fill that can be related to relatively minor variations in climate or tectonic activity (e.g., Schumm, 1977; Bull, 1991). Even under present climatic conditions, rare and infrequent flood events have the potential to cause significant erosion. It would be useful to examine conditions that are likely to lead to erosive phases, and the probabilities that these events might take place. Such erosive phases could destabilize hillslopes or change local base levels for streams headed on Yucca Mountain, thereby accelerating erosion near or over the proposed repository.

2. The potential for erosion of the alluvial fills is high. The alluvial fill represents unconsolidated material that could be eroded and transported relatively easily under some hydrological conditions. Because the hydrological conditions required for transport are largely unknown, it would be useful to evaluate the consequences of erosion of the channels to the depth of the alluvial fills. What impact would erosion of this magnitude have on the proposed repository?

3. Climate change involving higher mean annual precipitation over the period of regulatory concern could lead to higher rates of hillslope and channel erosion at Yucca Mountain. The TBR does not evaluate the potential impacts of climate change on erosion at Yucca Mountain. Yet climate change is possible over the period of regulatory concern. For example, recent research on global climate change suggests that a shift to more intense storm events might be a consequence of global warming (Karl et al., 1995). What impact would climate change have on hillslope and channel stability at Yucca Mountain?

4. Debris flows are significant erosive agents on the landscape. Debris flows are not considered to be major erosive agents under current climatic conditions, yet recent occurrences of debris flows are reported in the TBR. The TBR does not document the potential frequency and magnitude of these events, however, or report the ages of debris flow deposits. Debris flows can be an effective mechanism for hillslope erosion since such flows can leave depressions on hillslopes that can develop into stream channels. How effective are debris flows as erosive agents on the hillslopes at Yucca Mountain under current climate conditions? What effects would possible climate changes over the period of regulatory concern have on the frequency and magnitude of debris flows?

5. The potential for erosion of the alluvial fills on the west side of Yucca Mountain is high. As noted previously, the TBR does not address the potential for erosion of the alluvial fills on the west side of Yucca Mountain (Figure 1.1). What impact, if any, would erosion of the alluvium in the Amargosa River Basin have on the proposed repository under present or reasonable future scenarios for climate change?

Testing to Discriminate Among Alternative Interpretations

It is probably not possible to demonstrate that the stream channels are in dynamic equilibrium and that alluvial valleys could not be eroded at some future time. Therefore, a *bounding calculation*[6] of erosion of the alluvial fills in the valleys to the depth of

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[6] In conventional scientific practice, bounding calculations are used to estimate likely upper or lower values of processes or phenomena (e.g., erosion rates) when observational data or theories are inadequate. Such calculations are usually made by using relevant information from other sources and professional

the bedrock should be made. The effect of such fluvial erosion on hillslope stability should also be evaluated. Removal of the valley alluvium could significantly increase gradients at the bases of hillslopes, which could lead to accelerated erosion of gulleys headed on Yucca Mountain or to increased debris flow frequency and magnitude. Such tests would significantly reduce uncertainties in potential for erosion at the site, particularly under scenarios for future climate change.

The identification of debris flow deposits in cores and valley sediments could be used to address their frequency of occurrence, volume of material transported, and spatial distribution. Surficial mapping, subsurface sampling, and dating studies could address the effectiveness of debris flows as agents of erosion at Yucca Mountain.

Summary and Conclusions

A significant deficiency in the TBR is a lack of discussion of the relationships among surficial deposits and mapped surfaces, the processes that formed these surfaces, and the choice of surfaces for age dating. A conceptual model of the possible interactions between hillslope erosion and fluvial erosion should be presented. Could fluvial erosion destabilize hillslopes in the Yucca Mountain area? What is the potential for debris flows or landsliding at the site as evaluated from the spatial and temporal distributions of these deposits?

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judgment to define plausible upper and lower limits to the possible values of the process that is uncertain.

The TBR appears to evaluate fluvial erosion in terms of minimum estimates. It assumes that stream channels are in dynamic equilibrium and, thus, unlikely to erode through the valley fills. The potential for fluvial erosion at the site should be evaluated in terms of bounding scenarios. For example, what would happen if the alluvial valley fills were eroded to bedrock?

DOE has not conducted a general program of research on erosion processes and rates. Instead, efforts to evaluate erosion have focused on two topics: (1) an evaluation of the alluvial history and the potential for channel incision in Fortymile Wash and its tributaries, and (2) an evaluation of the ages of hillslope deposits on Yucca Mountain and Skull Mountain (discussed later in this chapter). The TBR offers no justification for the decision to evaluate the erosion potential of Fortymile Wash and its tributaries and to ignore the drainages on the western side of Yucca Mountain. Similarly, the rationale for examining the ages of heavily varnished hillslope deposits rather than a systematic study of the major hillslope units, including debris flow deposits, is not presented.

REVIEW OF QUATERNARY GEOCHRONOLOGY

Section 4.3 of the TBR (see Table 1.1) discusses Quaternary geology. The focus of this discussion is on the determination of ages of colluvial boulder deposits on the flanks of Yucca Mountain and Skull Mountain. The hypothesis presented in the TBR is that these boulder deposits have been relatively stable and that "channels" incised into the hillslopes adjacent to them (see Table 4.4.2-1 and Figure 4.3.2.1-2 in the TBR) can be used to approximate long-term erosion rates by means of the following formula:

$$\text{Erosion Rate} = (\text{Depth of Hillslope Channel})/(\text{Age of Colluvial Boulder Deposit}) \quad (2.1)$$

The TBR relies almost exclusively on cation ratio dating (CRD) to date the exposure ages of colluvial boulder deposits. This method involves measurement of the ratio

$$(Ca + K)/(Ti \pm Ba) \quad (2.2)$$

in the manganese- and iron-rich rock varnish formed on boulder surfaces, which has been shown to vary inversely as a function of age (Dorn, 1983; Harrington and Whitney, 1987).

Section 4.3 of the TBR is almost identical to a section from the DOE topical report on extreme erosion (DOE, 1993). The Nuclear Regulatory Commission reviewed this topical report (USNRC, 1994). Many of the issues discussed in the following sections are also addressed in the USNRC review.

Adequacy of Data Collection and Analysis

The committee's review of the adequacy of data collection and analysis focuses on the following three aspects of the discussion in the TBR: (1) criteria used to select CRD methods for surface exposure analysis; (2) the calibration, accuracy, and precision of the method; and (3) the types of deposits selected for CRD and erosion estimates. The following sections address these issues.

Criteria for Selecting CRD

The rationale for selecting CRD for geochronology (see p. 4-4 to 4-6 of the TBR) was that it could be applied to boulder deposits having a range of Quaternary ages. The committee understands that the decision to select the CRD method was made in the mid-1980s. At that time, a number of other techniques for surface exposure dating were being developed (notably, ^{36}Cl, ^{10}Be, ^{26}Al, and ^{3}He) but were not yet readily available for use. These methods have come into general use only in the past few years.

A number of statements made in the TBR concerning the selection criteria for CRD are not well justified. These include the following:

1. Alternate methods to date soils (i.e., U-series dating of carbonates) were not utilized because they provide "a minimum limiting age for the hillslope surface" (TBR p. 4-5). However, U-series dating has been used extensively in surface mapping efforts (**Paces et al., 1994; Lundstrom et al., 1995**) and could be useful in providing estimates of erosion rates. Analysis of soil ages would have provided complementary erosion rate data that are not dependent on assumptions concerning the origin of the boulder deposits.

2. The use of cosmogenic nuclides was excluded because they were not considered applicable to the relevant lithologies (quartz-rich tuffs and basalts; TBR point 3, p. 4-5). Both preliminary results presented to the committee on the field excursion and published information (e.g., Cerling, 1990; Poths and Crowe, 1992; Zreda et al., 1993; **Crowe et al., 1994**; Wells et al., 1995) suggest that cosmogenic nuclides are applicable in surface dating

studies at Yucca Mountain. Indeed, surface exposure dating is now applied widely in the study of Quaternary processes (Beck, 1994).

3. CRD was selected to avoid the problems of "inheritance" from exposure prior to deposition (TBR point 6, p. 4-6), which would produce unrealistically old ages for cosmogenic nuclide methods. In the case of cosmogenic techniques, the importance of prior exposure can frequently be evaluated by sampling at depth in the deposit or by measuring several nuclides with different half-lives (see Lal, 1991, for a discussion of cosmogenic isotopes and inheritance). Inheritance problems are also possible with varnish formation. In fact, inheritance is a general problem with all surface dating techniques.

The TBR implies that CRD is the best technique for estimating surface ages in the vicinity of Yucca Mountain. The committee disagrees with the notion that any one technique could be chosen as the "best" in this area and believes that several different techniques should be applied.

Calibration, Accuracy, and Precision of CRD

Because the processes of varnish formation are complex, application of CRD requires the development of an empirical calibration curve.[7] The calibration curve used to calculate ages in the

[7] A calibration curve is obtained by plotting the cation ratios (Equation 2.2) from several surface deposits against the ages of those surfaces. The ages are determined by independent geochronologic methods. After this curve has been established, an unknown sample can be dated by measuring its cation ratio and plotting it on the calibration curve to obtain its age.

TBR is based on U-trend[8] and potassium-argon (K-Ar) dating of lava flows at Crater Flat and clasts of welded tuff on an alluvial surface at Fortymile Wash (Harrington and Whitney, 1987).

The calibration curve can introduce uncertainties and systematic errors in the determination of ages of colluvial boulder deposits. The committee could not evaluate these uncertainties and errors because neither the TBR nor the published literature present a detailed discussion of the calibration data. Varnish begins to form on surfaces some time after eruption of lava flows or deposition of alluvium. The interval of time between eruption or deposition and varnish formation is unknown. The age data for the calibration curve are also difficult to evaluate because the youngest ages were obtained by U-trend dating, which is not well understood, as noted in footnote 8.

Peterson et al. (1995) recently published a new CRD calibration curve for the Yucca Mountain region.[9] The calibration ages on this curve are significantly different from the ages for the curve used in the TBR (see Table 4.3.2.3-1 of the TBR). These calibration ages are given in Table 2.1 and are plotted in Figure 2.2. As shown in Figure 2.2, most of the calibration ages from Peterson et al. (1995) fall outside the range of uncertainties for the

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[8] U-trend dating is an empirical method that relies on the open-system behavior of the daughter isotopes of uranium within soils. Because the mechanism of open-system behavior is unknown, this technique is not widely used. This method is distinct from U-series disequilibrium dating, which relies on the closed-system behavior of thorium and uranium and their radioactive daughters.

[9] The primary differences between the calibration curve of Peterson et al. (1995) and that used by Harrington and Whitney (1987) are the number of points and the methods used to determine the calibration ages. Peterson et al. (1995) used ^{14}C methods to obtain calibration ages, whereas Harrington and Whitney (1987) used U-trend dating. Both sets of ages are from samples collected near Crater Flat.

calibration ages used in the TBR. This suggests that the uncertainties presented in the TBR are underestimates.[10]

The TBR also does not distinguish between the precision and the accuracy of CRD data.[11] The uncertainties in the age ranges presented in the TBR are based on the standard deviation of the measured cation ratios in varnish samples and reflect the analytical precision (i.e., reproducibility of measured cation ratios on duplicate samples from the same site) rather than the accuracy of the mean CRD (i.e., how close the measured age is to the actual age). There are many ways to obtain precise, but inaccurate, CRDs. Accuracy can be assessed by using multiple geochronologic techniques and bracketing CRD ages by using dates on related deposits.

Support for Technical Interpretations

The following discussion focuses primarily on the following two issues: (1) the cation ratio technique itself and (2) the selection of sites for dating.

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[10] The error estimates given in the TBR do not account for uncertainties in the calibration ages used to construct the calibration curve. Had these been included, the uncertainties in the cation ratio ages would have been significantly greater. The committee understands that efforts are now under way to recalculate the uncertainties for the data published in Harrington and Whitney (1987) to account for this additional error.

[11] The term *precision* refers to the degree of agreement among repeated measurements of a quantity such as the cation ratio. The term *accuracy* refers to the degree of agreement of a measurement of a quantity with its actual or real value.

TABLE 2.1 Comparison of Calibration Ages and Uncertainties from the TBR with Calibration Ages from Peterson et al. (1995)

Sample Number	Cation Ratio (Equation 2.2)	Age in TBR (ka)	Age Range in TBR (ka)	Recalculated Age (ka)[a]
YME-1	2.99	640	610-670[b]	568
YME-2	4.52	170	40-180	83
YMW-1	3.34	465	400-515	365
YMW-2	2.97	645	630-660	582
YMW-3	2.88	710	680-740	652
YMN-1	2.79	760	710-820	730
LSM-1	2.52	960	930-990	1,025
SKM-1	2.74	800	760-830	778
SKM-2	2.68	830	800-880	838
SKM-3	2.28	1,180	1,110-1,270	1,387
SKM-3A	2.49	990	960-1,030	1,065
BM-1	2.09	1,380	1,260-1,510	1,762

Note: ka = thousand years before the present.

[a] Based on the calibration curve of Peterson et al. (1995).

[b] This range is reported as 610-970 ka in the TBR, but as 610-670 ka in Whitney and Harrington (1993).

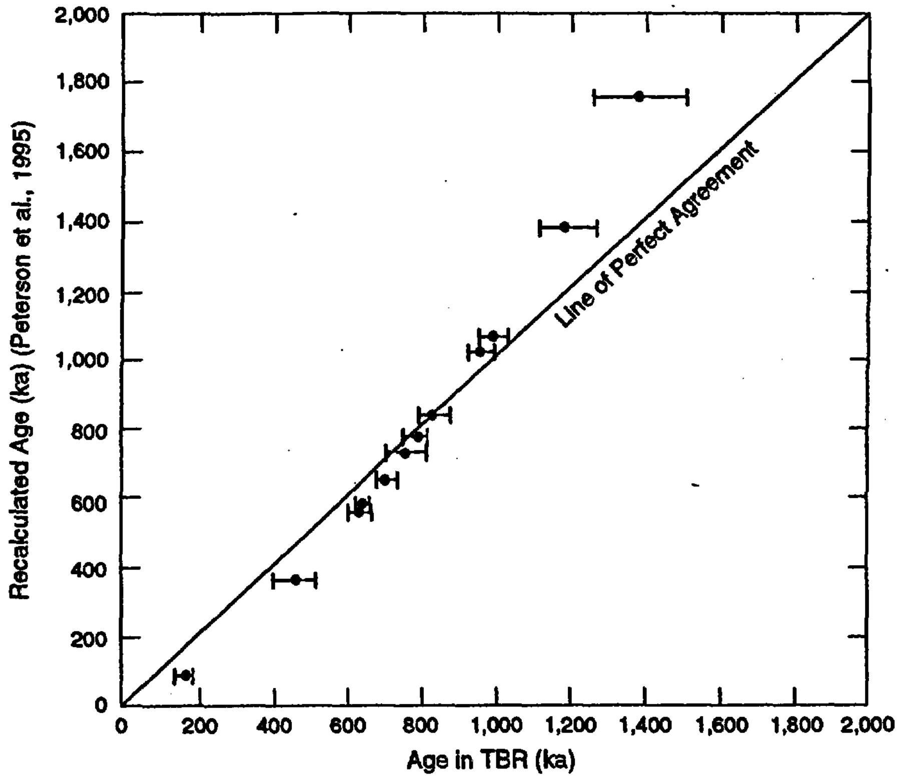

FIGURE 2.2 Graph comparing calibration ages and uncertainties from the TBR with the calibration ages of Peterson et al. (1995). The horizontal error bars indicate age uncertainties.

Cation Ratio Dating

There is considerable scientific disagreement with regard to all aspects of the CRD method–mechanisms of varnish formation, sample selection criteria, and analytical techniques for measuring cation ratios (e.g., **Dorn and Krinsley, 1991**; **Reneau and Raymond, 1991**; Bierman and Gillespie, 1994; Bierman and Gillespie, 1995; Dorn, 1995; Harrington and Whitney, 1995). A comprehensive discussion of CRD is beyond the scope of this review, but several issues merit comment.

The procedures used to obtain cation ratio dates introduce a systematic bias toward older ages, and the tabulated ages in the TBR probably represent maximum ages for the reasons noted below. The following procedures are of particular interest in this regard:

1. Colluvial boulder deposits were selected for geochronologic analysis because they were considered the most stable and thus the oldest surfaces at Yucca Mountain.

2. Field selection of samples for CRD analysis was based on the appearance of the varnish (i.e., color, thickness, and reflectivity; see **Harrington and Whitney, 1987**), which may preferentially select for the older clasts in a mixed population (Dorn, 1994).

3. Cation ratios are measured on six spots from each sample by using a scanning electron microscope with an energy dispersive x-ray attachment. The highest cation ratio of the six is discarded on the assumption that many processes can contribute to the development of high cation ratios (i.e., younger ages),

whereas artifacts contributing to low cation ratios (i.e., older ages) are rare (Harrington and Whitney, 1987).

The TBR argues that the cation ratio dates represent *minimum* ages, which may not be correct for the reasons noted above.

There are other controls on varnish chemistry that can introduce both random and systematic errors in age determinations. The iron-manganese crusts on the boulders can incorporate airborne dust, resulting in anomalous cation ratios. Substrate chemistry, microbial activity, vegetation, and local climatic conditions may also affect varnish chemistry (Krinsley et al., 1990; Reneau et al., 1991; Reneau et al., 1992; Krinsley et al., 1995). Indeed, the calibration curves for Yucca Mountain are distinct from those at Espanola Basin, possibly due to climatic differences (Harrington and Whitney, 1987). This suggests that a calibration curve must be generated for each locality. There is also evidence that the varnish layers are heterogeneous, perhaps as a result of past climatic changes during exposure (Krinsley et al., 1995). The TBR does not discuss or evaluate any of these issues. Considering the large number of published papers evaluating the strengths and weaknesses of CRD, the committee believes that these issues should receive more comprehensive discussion.

Choice of Sites for Cation Ratio Dating

According to the TBR, dating of heavily varnished colluvial boulder deposits on the hillslopes of Yucca Mountain and Skull Mountain is the most reliable means for estimating long-term erosion rates (see also Whitney and Harrington, 1993). However, some investigators have suggested that these boulder deposits were formed by deflation of the underlying surface over time (Dorn and Krinsley, 1994; Wells et al., 1995). If this interpretation is correct, the CRD data presented in the TBR represent maximum ages and minimum erosion rates. As noted earlier, sample selection and analysis protocols may also select for maximum ages.

The method for calculating erosion rates assumes that the channels adjacent to the colluvial boulder deposits were produced by hillslope erosion (see Figure 4.3.2.1-2 of the TBR). It also assumes that no erosion occurred on the boulder deposits. Post-depositional modification of the hillslope could minimize the relief adjacent to the colluvial deposits (e.g., by mass wasting), which would make the calculated erosion rates less than maximum values.

The greatest uncertainty associated with the erosion rate calculation in the TBR is the assumption that a single type of deposit can yield representative estimates of long-term erosion rates at Yucca Mountain. Erosion may occur over different time and spatial scales, and proper characterization of past erosion requires consideration of a variety of possible mechanisms, as discussed in the next section.

Credible Alternative Interpretations

The TBR should address several important alternative hypotheses that emerge from the foregoing discussion:

1. The ages determined for the heavily varnished boulder deposits do not reflect the duration of stability of the hillslopes. It is possible that the colluvial boulder deposits are relatively recent

features and have relatively old CRD ages because the varnish formed, or began forming, prior to their "deposition" in their present positions on the hillslope (e.g., Dorn and Krinsley, 1994; Wells et al., 1995).

2. The erosion rates calculated from the hillslope deposits (if one assumes, for the moment, that the CRD calibration curve is correct and no sampling bias has been introduced) are not representative of hillslope erosion rates at Yucca Mountain. The calculation of erosion rates assumes that the small amount of relief adjacent to the colluvial boulder deposits represents the total erosion on the hillslope (e.g., Figure 4.3.2.1-2 in the TBR). However, the original configuration of the hillslopes is unknown. The boulder deposits could have been deposited in small channels, and subsequent erosion could have inverted hillslope topography.

3. Erosion rates at Yucca Mountain are spatially variable. The approach used in the TBR assumes that erosion rates estimated from the colluvial boulder deposits can be used to characterize an "average" erosion rate for the entire region. However, it is well known from studies of other regions that erosion occurs at different rates in different areas (e.g., stable hillslopes versus faulted hillslopes versus stream drainages) and that erosion may be episodic rather than constant through time.

Testing to Discriminate Among Alternative Interpretations

A number of important tests could be performed to evaluate the alternative hypotheses:

1. Given the importance of CRD to the TBR and the uncertainties involved in the technique, additional geochronologi-

cal techniques should be applied to validate the CRD method and obtain independent age estimates. A number of independent dating methods are applicable to the boulder deposits, including ^{10}Be and ^{3}He methods. Both methods should apply over the age range in question. The shorter-lived cosmogenic nuclides ^{14}C, ^{26}Al, and ^{36}Cl may not be suitable, but could be used if the ^{10}Be and ^{3}He ages are significantly younger than indicated by the CRD method. The committee notes that ^{3}He and ^{36}Cl methods have been used to estimate exposure ages of lava flows at Lathrop Wells Volcanic Center (Crowe et al., 1992; Poths and Crowe, 1992; Zreda et al., 1993; Crowe et al., 1994) and appear to provide consistent results.[12] On the other hand, comparisons of CRD on Buckboard Mesa with ^{36}Cl dates (TBR section 4.3.3) differ by a factor of approximately two to four.[13] Clearly, more comparative work is needed to check the CRD results.

2. It should be possible to determine the spatial variability of erosion rates by applying other geochronological methods to a variety of hillslope and alluvial surfaces. For example, cosmogenic nuclide measurements from the top of Yucca Mountain could be used to calculate local erosion rates, independent of geomorphological assumptions.

3. The hypothesis that an erosion rate calculation obtained from a single type of deposit (colluvial boulders) is sufficient to characterize the regional erosion rate could be tested by applying

[12] Exposure ages of the lava flows at Lathrop Wells are estimated to be 48-73 ka for ^{3}He dating with an absolute uncertainty of about 30% (Poths and Crowe, 1992) and 75-85 ka for ^{36}Cl dating (Zreda et al, 1993).

[13] The estimated mean CRD age of Buckboard Mesa is given as 1,380 ka in Table 4.3.2.3-1 of the TBR, versus 310-600 ka for the ^{36}Cl ages given in Section 4.3.3. However, the TBR notes that the latter ages are somewhat problematical owing to near-saturation of ^{36}Cl in some of the rocks.

different calculation methods, as discussed in more detail in the next section.

Cosmogenic isotopic methods have come into their own only in the past few years. They can yield ambiguous results unless they are applied carefully and are interpreted within the geological context of the region. The integration of this geochronological work with surficial mapping is essential to provide the necessary context and control for interpreting the surface ages.

Summary and Conclusions

The lack of critical discussion of the uncertainties and assumptions of CRD is a significant deficiency of the TBR. The focus of the TBR on the precision of CRD, when accuracy is more important for the overall conclusions, is also problematic.

The erosion rates at Yucca Mountain appear to be extremely low under current climatic conditions on the basis of the data presented in the TBR. However, the TBR does not effectively make the case that these rates are representative of the region, because it relies on a single type of hillslope deposit and a single method for age determination. Estimates of erosion rates should be made by using a variety of approaches, as discussed above and in the next section.

There are a number of ways of testing the interpretations and conclusions presented in the TBR. None of these were presented or discussed. Different dating techniques, such as ^{3}He and ^{10}Be, could be applied to the colluvial boulder deposits to check CRD results. Additional dating studies of other geomorphic surfaces, as well as other methods for the erosion rate calculations, should be utilized in order to obtain estimates of the spatial variability of erosion rates at Yucca Mountain.

REVIEW OF EROSION RATES

Sections 4.1-4.2 and 4.4-4.7 of the TBR (see Table 1.1) provide a discussion of erosion. The focus of this discussion is on estimating long-term rates of erosion at Yucca Mountain. The TBR employs a numerical approach to characterize erosion. It calculates a numerical erosion rate for two types of erosional processes operating at selected sites at Yucca Mountain. The TBR then generalizes these numbers to infer the long-term average erosion rate applicable to the ground surface overlying the proposed repository.

Adequacy of Data Collection and Analysis

Calculation of erosion rates for Yucca Mountain is based on a standard geomorphic rate formula that is a generalization of Equation 2.1:

$$\text{Process Rate } (R) = \text{Process Magnitude } (M) / \text{Time of Process Operation } (T) \qquad (2.3)$$

The numerical values obtained from applying this formula to selected sites and processes are used to infer average erosion rates at Yucca Mountain. The TBR devotes considerable attention to the determination of surface ages that represent parameter *T* in Equation 2.3, as discussed in the previous section.

The TBR uses this rate formula without critical analysis. It is well documented that apparent geomorphic process rates (*R*) depend on the time scale (*T*) over which process operation is determined (Gardner et al., 1987). This dependence is such that rates for a given process determined over relatively short time intervals are generally much higher than rates determined over relatively long time intervals. Reasons for this variation have to do with the natural variability of processes over time and space. For example, many processes vary in rate through time. They are more rapid in certain time intervals, such as periods of active tectonic uplift, and less active in other intervals, such as periods of tectonic quiescence. Processes may also be cyclic in character, such as the cut and fill cycles of aggradation and degradation in drainage systems. Calculation of a single rate (*R*), over an arbitrary time interval (*T*), completely ignores the relevant time scales of these variations.

The TBR's analysis of longer-term erosion rates (*R*) via Equation 2.3 focuses on two specific processes: (1) hillslope erosion associated with heavily varnished (and presumably ancient) colluvial boulder deposits, and (2) stream incision along the major drainage (Fortymile Wash), which presumably provides local base level control for drainage off the eastern side of Yucca Mountain. The heavily varnished boulder deposits are a common though not ubiquitous feature on the hillslopes of the region. They are particularly prominent along the escarpment at the western side of Yucca Mountain.

Determination of process rates for hillslope erosion and stream incision would conceptually appear to bracket the potential for future erosion of Yucca Mountain, which might be envisioned to involve (1) escarpment retreat from the west or (2) headward drainage extension from the east, dictated by the base level of erosion established by incision of Fortymile Wash. The understanding of these relationships by readers of the TBR would be facilitated by inclusion of a simple cross section showing elevations of the land surface of Crater Flat, Yucca Mountain, and Fortymile Wash; the proposed repository; the water table; and other pertinent features. Figure 1.4 is an example of the kind of graphic that the TBR should have included.

Support for Technical Interpretations

The analysis of erosion rates in the TBR was performed on colluvial boulder deposits at Yucca Mountain, Little Skull Mountain, Skull Mountain, and Buckboard Mesa (see TBR Table 4.4.2-1). In addition, an analysis of erosion rates was made on sequences of terraces along Fortymile Wash on which age dates have been obtained. The colluvial hillslope deposits are not the only kind of hillslope feature in the region, nor are they necessarily representative of hillslope erosion rates. They may well occur at local sites representing some of the lowest long-term erosion rates in the region. There may be other areas at Yucca Mountain that are eroding at much higher rates than these stable hillslopes, as discussed later in this section.

The TBR reports incision rates for Fortymile Wash that are based on time intervals (*T*) determined through U-trend dating, which, as noted previously, is now considered highly problematic. New dating results presented to the committee during the information-gathering sessions need to be incorporated into the calculations made in the TBR. Furthermore, the TBR assumes that the terraces represent continuous time sequences; they could have been deposited over relatively short time periods, with long intervening periods of no deposition.

The TBR makes a useful comparison of Yucca Mountain erosion rates, presumed to be represented by the ancient colluvial boulder deposits, to erosion rates from other parts of the world. The hypothesis of exceedingly low long-term erosion rates at Yucca Mountain (approximately 2 mm/ky or 2 m/My; TBR, Table 4.4.2-1)[14] is comparable to the extremely low erosion rates known from ancient cratonic landscapes of the Gondwanaland continents, for example, Australia and southern Africa (Young, 1983; Bishop, 1985). DOE's conclusion that erosion rates at Yucca Mountain, which is part of the tectonically active Basin and Range Province of western North America, are comparable to rates for the ancient landscapes of the Gondwanaland continents is a fascinating scientific hypothesis. The committee believes that this hypothesis needs to be examined with some care and corroborated with additional data.

Tectonically active areas, regardless of climate, typically have long-term, average erosion rates of 1,000 mm/ky or 1,000 m/My (Summerfield, 1991)—although rates may vary locally by several orders of magnitude depending on tectonic setting and activity and the time scale over which such rates are measured (Ollier, 1981). The hypothesized long-term average erosion rates at Yucca Mountain are only a fraction of this rate according to the

[14] The TBR reports erosion rates by unit designations that are unconventional. Erosion rates are reported in units of cm/ka. The unit "ka" means "thousand years before present" and thus applies to ages, not time intervals. The proper unit for time intervals is "ky," which means "thousand years." The convention in geomorphology is to report erosion rates in millimeters rather than centimeters. This designation would promote comparison to the published literature in which erosion rates are typically reported as mm/ky or m/My (where My = million years).

data presented in the TBR. Is Yucca Mountain a region of unusual long-term stability within a larger, tectonically active region characterized by more rapid denudation? Such stability is certainly possible, because extension in the Basin and Range province is nonuniform and erosion is quite variable. What other data, besides the limited number of site-specific erosion formula calculations, are consistent with this interpretation of long-term stability? Consideration of these questions is essential to demonstrate that Yucca Mountain is indeed a long-term stable block in this otherwise tectonically active region.

Credible Alternative Interpretations

Perhaps the most compelling alternative hypothesis, which is based on general understanding of erosion rates in western North America, is that long-term erosion rates at Yucca Mountain are much higher than those cited in the TBR. Another alternate hypothesis, which is applicable to landscapes of high apparent stability (Twidale, 1976, 1991), is generally termed the "hypothesis of unequal erosion." This hypothesis holds that major elements of a landscape, particularly plateau surfaces and adjacent hillslopes, may exhibit very low rates of erosion, while adjacent elements, usually incised stream valleys, exhibit extremely high rates of erosion. A corollary of this hypothesis is that the zones of high erosional rate may migrate—for example, by headward stream erosion—into the zone of stability. Does this hypothesis apply to Yucca Mountain? Can this hypothesis be falsified? Note that this hypothesis introduces a mode of erosion—headward cutting of the stream channels—that is potentially applicable to the eastern and western sides of Yucca Mountain but is not explicitly discussed in the TBR. Figure 1.4 shows that the elevation of the upper block of the proposed repository is about 200 feet (approximately 60 m) above the bedrock-alluvium contact in Fortymile Wash. Removal of this alluvium and initiation of headward erosion on the east side of Yucca Mountain could potentially unroof the repository.[15] It is therefore essential to understand the overall pattern of erosion in time and space, and credible scientific evidence needs to be offered that this understanding applies over the time scale of regulatory interest.

Testing to Discriminate Among Alternative Interpretations

The focus of the TBR on ancient colluvial hillslope deposits and on the incision of Fortymile Wash ignores a variety of alternative approaches for determining regional erosion rates. The hypothesis that such sites represent the long-term erosion rate for the entire region, and specifically for the ground surface overlying the repository, needs to be tested. Such tests might involve estimating erosion rates at a few other hillslope sites in the Yucca Mountain region that are not mantled with heavily varnished colluvial boulder deposits. Examples of such sites include incised gulleys and stream channels that drain Yucca Mountain and show indications of more rapid erosion. Comparison of erosion at such sites can serve as bounding calculations to test the interpretations and conclusions presented in the TBR.

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[15] The distance between Fortymile Wash and the eastern edge of the upper block of the repository is approximately 6.1 km or 3.8 miles (TBR Figures 2.3-1 and 4.1.1-1). Headward erosion from Fortymile Wash into the upper block of the repository could be accomplished by a stream having a gradient of approximately 10 m per kilometer (53 feet per mile). The present-day gradient of Fortymile Wash (calculated from Figure 2.1 of this report) ranges from about 7.6 m per kilometer (40 feet per mile) near Highway 95 to about 13 m per kilometer (68 feet per mile) east of Yucca Mountain (see Figure 1.1).

The committee believes that a much better understanding of erosion rates at Yucca Mountain could be obtained by applying a number of different methodologies and evaluating their sensitivities to reasonable ranges of geological parameters. In this approach, "valid" solutions are those that fit all of the methodologies, and failures in agreement among the methodologies can be just as informative as successes. The calculation of erosion at a variety of hillslope sites in order to obtain a regional and temporal context for erosion is only one of several methodologies that could be applied. Other methodologies that may be applicable are the following: (1) calculation of long-term sediment budgets for drainage basins on and near Yucca Mountain; (2) topographic reconstruction of the known pre-erosional landscape and determination of the amount of degradation necessary to explain its present form; and (3) simulation of long-term landscape evolution employing quantitative modeling of hillslope and channel processes deduced from first principles.

The following material offers brief comments on these alternative approaches. The committee wishes to emphasize that these suggestions are merely illustrative of the kinds of tests needed to reduce uncertainties in the estimates of erosion rates presented in the TBR.

1. *Sediment Budgets*. Sediment-budget studies focus on the accounting within natural drainage systems for sediment sources, sinks, and transfers through time. This accounting procedure balances rates of erosion against the time scales and volumes of sediment accumulation. Thus, it automatically tests the consistency of inferred erosion rates with the natural process of landscape evolution.

2. *Topographic Reconstruction.* The discussion of drainage evolution (Section 2.5.1) and long-term channel erosion rates (Section 4.4.3.2) in the TBR suggests the potential for reconstructing the topography of ancient landscapes at Yucca Mountain. Well-dated volcanic sequences are known in the region. These include the Tiva Canyon Tuff (12.7 Ma[16]), the Thirsty Canyon Group (9.4 Ma), and the Buckboard Mesa basalt flows (2.8 Ma). From a digital topographic model (DTM) of the original landforms associated with these dated landscape elements, it should be possible, by subtracting the DTM for the modern landscape, to determine an erosion volume. Variations in the rates of process operation will have to be considered within these long time intervals.

3. *Simulation Modeling.* Geomorphic process simulation modeling, used in combination with data-intensive studies, may also be helpful in characterizing long-term erosion. As pointed out in the report *Rethinking High-Level Radioactive Waste Disposal* (National Research Council, 1990, p. 4), such ". . . models are vital for two purposes: (1) to understand the history and present characteristics of the site; and (2) to predict its possible future behavior." The simulation output will have to be carefully compared to measured erosion rates, sediment budgets, landscape reconstructions, and other relevant data. The simulations might function as "thought experiments" comparing alternative conceptualizations of the physical processes controlling regional landscape evolution and making predictions that can then be tested against observations.

[16] Ma = million years before present.

These alternative approaches will be especially useful for fitting the erosion rate estimates at Yucca Mountain into a regional context. The committee believes that this regional context is essential for demonstrating that Yucca Mountain is indeed an area of exceptional erosional stability.

Summary and Conclusions

The focus of the TBR is on temporally and spatially averaged erosion rate estimates for comparison against a regulatory standard. The TBR presents its conclusions with little discussion of whether all credible alternative interpretations have been considered and eliminated on the basis of appropriate scientific testing. The TBR relies on specific Quaternary geochronological tools that are not widely used (U-trend dating) or are highly problematic in the light of current scientific understanding (CRD), as noted previously. The TBR devotes too much attention to analysis of a single dating tool, cation ratio dating, and does not give enough consideration to the many alternative approaches possible for Quaternary geochronology. As noted earlier in this chapter, a combination of geochronological tools is essential for the comparisons necessary to evaluate age uncertainties and to establish scientific credibility.

Whatever the limits on dating uncertainties, the measurement of geomorphic processes and their effects over a variety of time scales is necessary to distinguish cyclic phenomena, such as those associated with climatic change, from other patterns. The entire range of erosion processes operating on the landscape needs to be characterized in terms of local effectiveness and the spatial variability of that effectiveness. If there is spatial and temporal variability of erosion rates, then analysis must be made of the pattern of this variability and how it evolves over the time scales of regulatory concern. By focusing on a single calculated value, presumed to represent some spatially and temporally averaged regional erosion rate, the TBR fails to establish credibility in the scientific basis for numerical characterization of erosion.

The uncertainty in that characterization is not solely a matter of measurement error in laboratory elemental abundance determinations (for geochronological quantification of time intervals) or in incision depth measurements (for quantifying process magnitudes). The major scientific uncertainties derive from concerns that portions of the landscape may be eroding much faster than those cited in the TBR; that processes not considered by the TBR may be important; and that the causes, regional patterns, and temporal variability of erosion at Yucca Mountain may not be understood.

It is perhaps appropriate to close this chapter with a comment to DOE program managers: The committee is not recommending that the DOE undertake an extensive or expensive program of research on erosion at Yucca Mountain. Indeed, based on the information received during its information-gathering sessions, the committee suspects that much of the needed work is already under way (e.g., cosmogenic isotopic dating of some hillslope deposits), or that the needed data are already at hand or available in the literature (e.g., data for estimating regional erosion rates). Some new data collection may be necessary to estimate erosion rates of younger hillslope or fluvial deposits. The committee believes that some additional effort is essential to make a scientifically credible case for the low erosion rates at Yucca Mountain.

3
PRECLOSURE HYDROLOGY

This chapter provides a review of the sections of the technical basis report (TBR) related to preclosure hydrology, including flooding potential, ground water conditions in the unsaturated zone, and water resource potential. These issues are discussed in Chapters 2 and 3 of the TBR (see Table 1.1 of this report), but are grouped and discussed together in this chapter because they address a common topic—the potential impact of hydrology on the proposed repository during construction and operation.

The preclosure hydrology sections of the TBR address the following three questions:

1. Can surface floods enter the access tunnels or shafts or jeopardize surface operations at the portals during construction and operation of the proposed repository?
2. Can the repository be constructed, operated, and closed by using reasonably available technology to control ground water intrusions?
3. Is the ground water supply at Yucca Mountain sufficient to provide for the needs of the proposed repository during construction and operation?

REVIEW OF SURFACE FLOODING

The potential for surface flooding at Yucca Mountain is discussed in Section 2.6 of the TBR. The focus of this discussion is whether the proposed repository can be constructed, operated, and closed using reasonably available technology[1] (RAT) to protect against surface flooding. The TBR presents estimates of the water surface elevations associated with the probable maximum flood (PMF) to demonstrate that flooding does not pose a threat to three repository facilities: (1) Shaft Site No. 2, which is potentially affected by flooding in Drillhole Wash or Coyote Wash; (2) South Portal Site and Pad, which are potentially affected by flooding in an adjacent wash; and (3) North Portal Site and Pad, which are potentially affected by flooding in Midway Valley Wash (see Figure 2.6.2-1 of the TBR and Figure 1.2 of this report).

The probable maximum flood is an estimate of the largest flood that can occur at a site under current climatic conditions. The PMF is estimated by using a number of very extreme or upper bounding values for precipitation and runoff. The PMF procedure is used routinely by engineers in the design of flood-prone engineering structures such as dams.

Estimation of the PMF for a site can be envisaged as a three-step process: (1) the probable maximum precipitation (PMP)[2] event at the site is estimated by using extreme but possible events based on regional weather records; (2) surface runoff and the resulting streamflow from this precipitation event are calcu-

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1 The term *reasonably available technology* is not defined in the TBR. The committee understands this term to mean technology in use in other applications, such as mining, that can be adapted for use at the repository.

2 PMP is the greatest depth of precipitation that can occur over a given drainage area for a specified duration of time.

lated; and (3) the flow depth at selected channel cross sections is estimated from this discharge.

PMFs for selected areas at Yucca Mountain were estimated using these procedures. Precipitation estimates for Yucca Mountain were taken from a National Weather Service report (NWS, 1977) that provides PMP estimates for the Colorado River and Great Basin drainages. The PMP event estimate was used to calculate the volume of runoff from specific drainage areas at Yucca Mountain. Unit hydrographs[3] were developed based on the standardized regional flood graphs for the southwestern United States used by the U.S. Army Corps of Engineers. The unit hydrographs and runoff estimates were then used to generate flood hydrographs for a number of drainages. The flood hydrographs were estimated by using standard Bureau of Reclamation procedures as described by Bullard (1991). The maximum discharge rate on the hydrograph is called the *peak discharge rate,* the *peak discharge,* or the *peak runoff rate.* This peak discharge rate was converted to a depth of flow at selected stream channel cross sections through flood routing procedures, which require estimates of water velocity and channel roughness. The maximum predicted depths of flow at these cross sections were compared directly to the elevations of the portals, pads, and shaft to determine their flooding potential.

The procedures used to estimate the PMP and peak discharge rates are relatively straightforward engineering calculations. However, flood routing is less standardized and requires expert judgment in the estimation of input parameters to a hydraulic

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[3] A hydrograph is a plot of stream discharge (in units of volume of water per unit time, for example, cubic feet per second) against time. A unit hydrograph is the normalized discharge resulting from a specified rainfall of specified duration. These normalized unit hydrographs are used to generate flood hydrographs for specific storm events.

simulation model, in this case the Flood Hydrograph and Routing algorithm of the Bureau of Reclamation. The critical parameters of interest in the model are a hydraulic resistance coefficient, called Manning's *n*, and the Froude number, a physically significant dimensionless ratio that determines the depth and velocity characteristics of the flow.[4] A third important input parameter to this model, the "bulking factor," is used to represent the effects of entrained sediment, air, and debris carried by the flowing water on the flow depth.

Adequacy of Data Collection and Analysis

The application of probable maximum flood procedures in the TBR to estimate flood events is consistent with practices used to design civil structures such as bridges and dams. However, the TBR descriptions of these procedures, particularly the data and assumptions used in flood routing and water surface elevation estimation, are too brief to allow evaluation of the adequacy of data collection and analysis. The committee had to consult references cited in the TBR (i.e., **Bullard, 1991**; **Blanton, 1992**; **Glancy, 1994**) to determine exactly which procedures and data were used. For example, the TBR does not mention an important assumption used in the calculations: namely, that critical flow depths are assumed in cases where the Manning equation[5] predicts supercritical flow velocities. The committee discovered this assumption during its review of the references cited in the TBR.

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[4] The Froude number characterizes flow as either subcritical (tranquil) or supercritical (shooting).

[5] The Manning equation is an empirical relationship that relates water velocity to channel roughness, depth of flow, and the slope of the energy grade line. The latter is usually assumed to be equal to the slope of the channel bed.

Support for Technical Interpretations

The TBR is limited in its descriptions of PMF calculations. Consequently, it does not provide explicit support for the details of the PMF procedure, including the runoff response, flood routing, and parameter estimates and assumptions. Estimates of PMF flows were made for several locations in the washes near the North Portal Pad, South Portal Pad, and Shaft Site No. 2 by using **Blanton's (1992)** procedure, which assumed a bulking factor of 2. Although not stated explicitly in the TBR, it appears that many calculations were based on a Manning's *n* value of 0.045. The assumption of critical flow velocity is conservative for this assumed value of Manning's *n* (as noted in the last section, critical flow depths were assumed in cases where the Manning equation predicted supercritical flow velocities). That is, the use of this Manning's *n* value with a critical flow velocity produces a greater flow depth (i.e., a "larger" flood) than would be expected under supercritical flow conditions.

Bounding curves for maximum peak discharge shown in Figure 2.6.3-1 of the TBR and those from **Glancy (1994**, derived from the equation given on p. 28 and the table on p. 29 of that paper) are generally consistent by a factor of 2 or less, except on very small watersheds. Given the nature of these kinds of calculations, these results seem reasonable to the committee.

It would have been helpful to readers to provide more discussion regarding the procedures and rationale for the selection of Manning's *n* value and the bulking factor. Also, the committee notes that the water surface elevations for the PMFs shown in Figures 2.6.2-1 and 2.6.2-2 of the TBR are difficult to interpret. Clearer graphics showing PMF elevations also would be helpful to readers.

Comparison of PMF peak discharge estimates (open square symbols in Figure 2.6.3-1 of the TBR) with the curve used to represent maximum regional floods (Figure 2.6.3-1, upper curve) shows that the PMF-based water surface elevations are conservative: that is, they provide maximum depths of flooding. Given the high level of uncertainty in estimating flood peaks in arid areas (e.g., by applying six methodologies, Glancy, 1994, p. 29, produced estimates with variations as great as a factor of 3 for a specific site), the differences in flood peak discharges using the methods cited in the TBR appear reasonable.

Figure 2.6.2-2 of the TBR shows that parts of the pad at the North Portal Site are within PMF inundation boundaries. The last two sentences of Section 2.6.2 of the TBR (p. 2-12) state, "A portion of the existing North Portal Pad to support ESF[6] operations is located in the flood-prone area (Figure 2.6.2-2). This will be further evaluated in the Guideline Compliance Assessment to ensure that RAT can mitigate potential hazards for the repository surface facilities." The committee was unable to determine whether this pad could be protected from flooding by using RAT, although such protection would appear to the committee to be relatively straightforward.

Credible Alternative Interpretations

An alternative hypothesis is that the PMF is significantly different than estimated because of uncertainties in runoff response, Manning's *n*, and the bulking factor. This could affect the interpretation of flooding potential at critical surface facilities at Yucca Mountain.

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6 Exploratory Studies Facility.

Testing to Discriminate Among Alternative Interpretations

The alternative hypothesis can be tested easily through sensitivity analysis of the estimated water surface elevations to assumed values of runoff response, Manning's *n*, and the bulking factor, and the assumption of critical flow depth at all locations in the stream channels. Bounding calculations involving the systematic variation of the Manning coefficient around the value of 0.045 assumed in the TBR and the bulking factor from 1.0 to more than 2.0 would show the sensitivity of estimated water surface elevations to the assumed values of these parameters. This would provide additional insight into the uncertainty of the estimated water surface elevations.

Summary and Conclusions

The use of probable maximum flood estimate procedures in the TBR is consistent with general engineering practice. Assumed values of runoff response, Manning's *n* (0.045 in all channels), critical velocity, and the assumed bulking factor of 2, while likely conservative, are not supported by data or documentation in the TBR. Nor were they justified by field measurement or citation to the literature in the references provided in the TBR. More documentation and explanation of procedures used to calculate PMFs are needed in the TBR, as are graphics to illustrate PMF elevations in relation to critical facilities.

More work should be done to assess the sensitivity of the estimated water surface elevations to the assumed values of Manning's *n* and the bulking factor, and the assumption of critical flow depth at all locations in the stream channels. This testing will provide additional insight into the effects of these assumptions on estimates of flooding potential at the sites of interest.

REVIEW OF SUBSURFACE FLOODING

A description of the unsaturated zone hydrostratigraphy at Yucca Mountain and the potential for intrusion of ground water into the proposed repository is addressed in Section 3.2 of the TBR. Subsurface water intrusions during repository construction and operation could conceivably arise from three sources: (1) deep percolation of infiltrating surface water through continuous cracks or fractures; (2) discharge of subsurface water under positive pressure stored above the repository (perched water); or (3) rise of the underlying water table to the level of the repository. Because the TBR deals only with preclosure issues, potential adverse effects are to be evaluated within the projected 50- to 100-year life of repository operation prior to closure.[7]

Adequacy of Data Collection and Analysis

The TBR does not explicitly address whether rising water tables or deep percolation of infiltrating surface water could cause flooding of the repository during the preclosure phase. Although neither of these two sources appears to the committee to pose a problem for construction or operation, the report should have demonstrated this. The percolation rate in this area is extremely

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[7] The estimated duration of the preclosure phase of the repository is not stated explicitly in the TBR. The 50- to 100-year estimate was provided to the committee at one of its information-gathering sessions.

low (Montazer and Wilson, 1984), and there is no evidence of steady deep seepage in appreciable amounts (Czarnecki, 1985). Substantial amounts of data have been collected on infiltration rates at the site, and age dating of water in the infiltration zone and water extracted during deep borehole construction has been attempted, but these data are not discussed in the TBR.

The proposed repository is to be located about 200 m (about 650 feet) above the present level of the water table, so significant volumes of recharge would be required to raise the water table level to the repository. It has been argued that there is historical evidence for mean annual precipitation amounts up to 100 percent above the current mean annual precipitation in the area (Spaulding, 1985). Modeling of the steady-state position of the ground water table for a doubling of mean-annual precipitation showed that the repository remained in the unsaturated zone, about 30 m (approximately 100 feet) above the final position of the water table (Czarnecki, 1985). However, it is worth noting that in these simulations, the predicted steady-state ground water recharge rate increased by up to a factor of 15 compared to present-day recharge.

A number of untested simplifying assumptions were made in this model. The model calculation assumed that the ratio of runoff to infiltration was identical to present-day conditions. The calculation also does not include the effects of increased precipitation on unsaturated zone fluxes through large flow channels or on perched water storage changes. A change in hydrologic response, such as decreased runoff with increasing precipitation (e.g., due to the retardation by vegetation), would have resulted in increased recharge. An empirical relationship between precipitation and recharge was also used in the model. This relationship has not been tested over the range of inputs used in the calculation. Further, the model predicts only the steady-state position of the water table. It does not address the question of how much time would be required for the water table to re-equilibrate after precipitation is doubled.

Thus, the model exercise has limited value for making quantitative estimates of water table responses to a doubling of mean annual precipitation. Because the time frame of the preclosure phase is short (50-100 years), water entry into the repository from infiltrating water does not appear likely. This could have (and should have) been demonstrated in the TBR.

Section 3.2.1 of the TBR describes the principal hydrostratigraphic units in the unsaturated zone of Yucca Mountain. The narrative descriptions of these units are probably adequate for the purposes of this TBR—although they rely on papers by Montazer and Wilson (1984) and Weeks and Wilson (1984), which were published prior to most of the detailed site characterization studies of the unsaturated zone. It would have been useful to include additional estimates of hydraulic conductivity, porosity, and water saturation that have been determined from more recent core sampling and borehole logging. The "conceptual" hydrogeologic section presented in Figure 3.2.1-1, which is based on the early work of Montazer and Wilson (1984), is grossly inadequate for evaluating the potential relationships between perched water zones and stratigraphic or structural features. An accurately scaled cross section that shows elevations of the land surface and locations of boreholes, the proposed repository, and the water table should have been provided in the TBR to facilitate understanding.

The TBR discusses the appearance of perched water in various boreholes and concludes that (1) all perched water is below the proposed repository depth, although it is possible that it could be encountered during construction and operation, and (2) perched water does not appear in sufficient quantity to constitute a problem that cannot be handled by RAT. The sources of information used to identify subsurface water storage are various deep boreholes in the vicinity of Yucca Mountain extending to the water table and shallow neutron access tubes confined to the surface alluvium. The methods of data collection appear to be up-to-date. Dry drilling technology was used to construct most of the boreholes, which eliminated drilling fluid contamination problems. Standard methods of isotope analysis were used estimate water ages. However, little of this information is provided in the TBR.

Support for Technical Interpretations

As noted above, the TBR concludes that perched water does not pose a problem for preclosure operations that cannot be solved by RAT, and the committee believes that this conclusion is reasonable. However, the TBR does not use available data to best advantage in drawing this conclusion, and some statements of questionable accuracy appear in the discussion. The brief discussion of perched water on pages 3-4 and 3-5[8] of the TBR would have been clearer and more effective if the report had included a figure showing the locations of the wells and the geologic cross sections identifying the perched water locations. The committee was shown a poster during the field excursion that would have been adequate for this purpose. The statement made in the TBR on page 3-4 that perched water was encountered 100 m (approximately 330 feet) above the water table in all cores is wrong, since UZ-14 encountered perched water at an altitude of 965 m (3,165 feet) above mean sea level (TBR, p. 3-5), which is some 187 m (613 feet) above the water table at that location and

[8] Note that pages 3-5 and 3-6 in the TBR are miscollated.

between 29 m (95 feet) and 87 m (285 feet) below the proposed repository.[9] This hole is about 1 km (approximately 3,300 feet) north of the site. The absence of graphics or even a comprehensive table summarizing perched water locations made it extremely difficult for the committee to discern the spatial distribution of perched water from the discussion in the TBR.

No attempt was made in the TBR to analyze perched water locations relative to geologic features in the unsaturated zone, even though such an analysis might assist in estimating its distribution and extent. The zones of perched water appear to occur above hydrostratigraphic units of lower permeability, which is logical, and may also accumulate at or near fault boundaries. Accurately drawn cross sections would have illustrated such relationships.

No information on perched water volumes or its rate of entry to the boreholes is provided in the TBR. Although most of the perched water discovered was insignificant in volume, wells UZ-14 and SD-7 produced large volumes of perched water [6,000 and 22,000 gallons (23,000 and 83,000 liters)] in short (67- and 90-hour) pumping tests. Moreover, the perched water in UZ-14 behaved as though it were part of a large reservoir (Burger and Scofield, unpublished manuscript cited in the TBR). This information could have been useful in making bounding calculations about the possible impacts of encountering perched water zones during repository construction and operation.

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9 The water table in UZ-14 is located at about 780 m (2,558 feet) above mean sea level according to information received by the committee during one of its information-gathering sessions. The elevation of the northern end of the repository is about 1,052 m (3,451 feet) above mean sea level for the upper block and about 994 m (3,260 feet) above mean sea level for the lower block, based on Figure 4.1.1-1 of the TBR.

The discussion of RAT is very brief and would have benefited from a discussion of water volumes typically encountered in mining operations and how they are handled. Rather than take an analytical approach, the TBR simply states that RAT could deal with any anticipated problems. The committee has made no attempt to evaluate RAT and merely notes that to enhance the completeness and credibility of the analysis, the TBR should explicitly address RAT in the context of the available information on perched water at the site.

Credible Alternative Interpretations

There are two places in which the TBR has glossed over points of relevance to the issues surrounding perched water. First, the extremely high water table levels in wells G-2 and WT#6 to the north of Yucca Mountain are never mentioned in the perched water discussion, even though one alternative interpretation for their existence is that they are in fact perched water, and not part of the regional water table (e.g., Ervin et al., 1994). The proposed location for the repository is at least 200 m (approximately 650 feet) above the water table that lies directly beneath it. However, the elevation of the water table in wells G-2 and WT#6 is about 20 m (66 feet) below the elevation of the northern end of the upper block of the proposed repository and about 36 m (118 feet) above the elevation of the northern end of the lower block of the proposed repository,[10] although at least 2 km (1.2 miles) north of the repository boundary.

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[10] The elevation of the water table in these wells is 1,029-1,035 m (3,375-3,395 feet) above mean sea level. As noted in footnote 9. the elevation of the northern end of the proposed repository is about 1,052 m (3,451 feet) above

The paper by Fridrich et al. (1994), which was not cited in the TBR, discusses several possible explanations for the apparent rise in water table elevation north of Yucca Mountain. These authors did not discuss perched water as one of the explanations, although it was proposed by Ervin et al. (1994), which also was not cited in the TBR. Interestingly, the water table elevations observed in wells G-2 and WT#6 are not too different from the elevation of perched water (965 m [3,165 feet] above mean sea level; TBR, p. 3-5) in the northernmost well (UZ-14) in which it has been detected.

The second omission in the TBR is the absence of any discussion of the age or genesis of the water found in either the perched water zones or the shallow neutron access holes. There is substantial information from ongoing tritium, ^{14}C, deuterium, strontium, uranium, and ^{36}Cl analyses of subsurface pore and perched water that suggests different hypotheses for the origin of this water. These data should have been discussed in the TBR, particularly as they bear on the rate of supply of water to the perched zones. The information obtained to date (which was presented to the committee at its information-gathering sessions) suggests that the perched water appears to be quite old. This information would have supported the conclusion that perched water is not a problem for preclosure and would have offered some assurance that the zones are not connected by short travel times to the surface.

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mean sea level for the upper block and about 994 m (3,260 feet) above mean sea level for the lower block.

Testing to Discriminate Among Alternative Interpretations

More work needs to be done to the north of Yucca Mountain to investigate the nature of the high water table in that area. By pumping wells G-2 or WT#6 and looking for discrete fractures refilling the pumped zone, it should be possible to determine whether the saturated zone is perched. This technique was used to identify the perched water in well UZ-14 (Burger and Scofield, unpublished manuscript cited in the TBR). The information that is used to delineate the high-water-table-gradient zone north of the repository location is very sparse, and the contour lines are subject to great uncertainty. The potentiometric surface determination would, therefore, benefit from an additional well placed in the high-gradient zone. The committee understands that both of these activities are currently under way at the site (Russ Patterson, DOE, personal communication).

Summary and Conclusions

Of the three potential sources of subsurface water that could flood the proposed repository (deep percolation, rising water table, and perched water), only the latter is discussed in the TBR. Inclusion of an analysis of the first two sources would have been possible, given the body of available information, and would have added to the completeness of the discussion.

The brief discussion of perched water in the TBR contains no analysis. The TBR should have included figures showing topography, geology, structure (e.g., faults), well locations, perched water, and the ground water table. It also should have provided quantitative estimates of perched water and data summaries of relevant information where available. It does not appear to the committee that perched water will pose problems that cannot be handled by RAT within the 50- to 100-year life of repository operation. Nevertheless, the TBR could have made far more effective use of existing information in making this point.

REVIEW OF WATER RESOURCE POTENTIAL

Water resource potential at Yucca Mountain is addressed in Section 3.3 of the TBR. The questions related to water resource potential are not stated explicitly in the TBR but can be inferred from information in other references. According to the early site suitability evaluation (Younker et al., 1992), two questions must be addressed to evaluate water resource potential:

1. Is adequate water for repository development available from surface or ground water sources?
2. Can legal rights to available water be obtained?

The second of these questions is outside the scope of a scientific peer review, although the answer to this question may depend on a technical evaluation of whether existing ground water resources in the area are being mined (i.e., being pumped at a rate that exceeds the long-term perennial or sustained yield of the aquifer). This report, therefore, concentrates on the first question related to analysis of ground water availability.

Another question related to preclosure water supply is whether the water is of sufficient quality for use at the repository site. The issue of water quality is not addressed in the TBR, presumably because water quality is known to be adequate or water quality is not of particular concern given its intended use at the repository site.

An explicit definition of the basic questions related to water resource availability is essential to judging the adequacy of data and syntheses; different types of data and different analyses would be required depending on the nature of the technical question. Adequacy of available ground water for repository needs can be assessed by either (1) accurate estimates of the total amount of water available for use or (2) a comparison of bounding estimates of water requirements to bounding estimates of water supplies. Some statements in the TBR suggest that the total available water is to be estimated, but other statements indicate that bounding estimates of requirements and supplies are the objective. It is not clear if "available water" is assumed to include all water in the aquifer or if available water is limited to that which could be produced without significant mining.

At least three aquifers could be tapped for water supply at Yucca Mountain: a shallow alluvial aquifer in Fortymile Wash, the tuff aquifer (shown on the cross sections in Figures 1.3 and 1.4), and a lower confined carbonate aquifer. The production rates and modeling results described in the TBR are only for wells completed in the tuff aquifer, implying that this is the aquifer that will be used to supply repository construction needs. However, the TBR makes no explicit statement that this is the only aquifer being considered for that purpose.

Adequacy of Data Collection and Analysis

This review of the adequacy of data collection and analysis focuses on three issues: (1) well and production data, (2) numerical modeling, and (3) water requirements for repository construction and operation. These issues are addressed in the following subsections.

Well and Production Data

The section of the TBR on water resources potential begins on page 3-6 with a review of water supply and monitoring wells within the Jackass Flats area (see Figure 1.1). Wells are described in a chronological narrative rather than in a tabulated summary, which hinders comparisons and spatial understanding. Production rates are reported in a variety of units (liters per second, gallons per minute, cubic meters per day, and acre-feet per year), which also makes direct comparisons difficult.

Many relevant and available well data are not discussed in the TBR. These include numerous data from wells completed as part of the Yucca Mountain site characterization project (e.g., Ervin et al., 1994), as well as regional water level data (e.g., La Camera and Westenburg, 1994). Water levels measured in these wells can provide important constraints on conceptual[11] and numerical models of the ground water flow system.

The TBR cites, without any supporting data, an estimate by Young (1972) of the interval of time required to dewater the aqui-

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[11] A conceptual model is a description of the distribution of aquifers and confining units, the location of recharge and discharge areas, and other important hydrologic properties and boundaries of the ground water system.

fer at a particular pumping rate. Given that considerable uncertainties still exist regarding the conceptual model of the flow system (Fridrich et al. 1994), this estimate may not be accurate.

The summary of annual production rates and periodic water level measurements from **La Camera and Westenburg (1994)**, which are shown in Figures 3.3-1 through 3.3-3 of the TBR, provides the most quantitative data on water availability in the vicinity of Yucca Mountain. The usefulness of this information would be enhanced by the inclusion of a map in the TBR indicating pumping and observation well locations and a cross section showing open intervals and production intervals of monitoring and pumping wells, respectively.

Numerical Modeling

The final section of the discussion of preclosure water supply refers to the simulation results of **Czarnecki (1991)**. These simulation results are presented without discussion of the conceptual model of the ground water system or of the data used to estimate model parameters. Although they are not presented in the TBR, basic data for conceptual model development and model calibration are discussed in publications describing the original numerical model developed by Waddell (1982) as well as in Czarnecki and Waddell (1984). These publications note that although there is a paucity of water level data north of the proposed repository, available data in this area indicate an anomalously steep gradient. Czarnecki and Waddell (1984) also note that there is a general lack of transmissivity data throughout the modeled area.

Water Requirements for Repository Construction and Operation

Use of the modeling results of Czarnecki (1991) to assess the adequacy of available water requires that the pumping rates simulated [up to 7 x 10^8 gallons per year (2.6 x 10^9 liters per year)] be related to those anticipated for repository construction and operation. No estimates of repository requirements are provided in the TBR. Table 3.1 of this report summarizes estimates of water requirements derived from values cited in other documents including the final environmental assessment (DOE, 1986), site characterization plan (DOE, 1988), the early site suitability evaluation (Younker et al., 1992), and a memorandum prepared by the Department of Energy (DOE, 1995) in response to committee questions. The wide range of these estimates suggests considerable uncertainty in the water requirements for the repository. In addition to estimates of repository water requirements, assessment of water availability may also require analysis of concurrent water demands (e.g., for irrigation) in adjacent areas that are part of the same regional aquifer system.

Support for Technical Interpretations

The first interpretation provided in the TBR is the cited estimate of 76 to 380 years (Young, 1972) to dewater the aquifer at a pumping rate of 1,000 gallons per minute (3,800 liters per minute) or >5 x 10^8 gallons per year (>1.9 x 10^9 liters per year). Potential problems with this estimate resulting from limitations of the model assumptions are noted in the previous section. The TBR itself questions this interpretation, noting that observed

TABLE 3.1 Estimates of Water Requirements for Repository Construction and Operation

Peak Rate (gallons per year) [liters per year]	Annual Rate (gallons per year) [liters per year]	Cumulative (gallons) [liters]	Reference
	1.14×10^8 [4.32×10^8]	3.7×10^9 [1.4×10^{10}]	**DOE, 1986**
1.2×10^8 [4.5×10^8]	1.15×10^8 [4.35×10^8]	$>3 \times 10^9$ [$>1 \times 10^{10}$]	**DOE, 1988**
$>1.8 \times 10^8$ [$> 6.8 \times 10^8$]		2×10^9 [8×10^9]	**Younker et al., 1992**
		1×10^8 [4×10^8]	1985 estimates, **Younker et al., 1992***
1.3×10^7 [4.9×10^7]			DOE, 1995
3.3×10^7 [1.2×10^8]			DOE, 1995
5.5×10^7 [2.1×10^8]			Current usage for ESF: DOE, 1995

* **DOE (1986)** and **Younker et al. (1992)** cite the same correspondence as a reference for these estimates. In **DOE (1986)**, the value 4.32×10^5 m^3 (4.32×10^8 liters) is called an "average annual consumption" for a 32 year construction and closure period, whereas **Younker et al. (1992)** refer to this same value as "water consumption for lifetime repository construction and operation."

recovery of water levels in a pumping well following decreases in pumping rate is inconsistent with Young's assumption of no recharge.

The TBR also concludes that the short-term effects of pumping on the regional potentiometric surface are negligible and that the tuff aquifer is experiencing regional recharge. This interpretation is consistent with reported recoveries of water levels during periods of reduced pumping and with the limited drawdowns observed during historic pumping. In discussing the water level monitoring data summarized in Figures 3.3-1 through 3.3-3, the TBR notes that these data suggest that no permanent drawdowns have been caused by ground water withdrawals to date in Jackass Flats. However, without additional information on the relative locations of pumping and observation wells, and without more extensive data on regional pumping rates and other ground water fluxes, it is difficult for the committee to evaluate this conclusion.

The TBR also cites a conclusion from Younker et al. (1992) that preclosure hydrology issues (presumably those related to water supply) can be accommodated by RAT. As in the case of the estimate of dewatering rates, no data or analyses to support this conclusion are included in the TBR. The water supply discussion in Younker et al. (1992) refers to an earlier environmental assessment (DOE, 1986), which cites a production rate of about 1.3×10^8 gallons per year (4.9×10^8 liters per year) for well J-13 over the period 1962-1983. The source of this production rate estimate is not provided. Thordarson (1983), one of the references cited in DOE (1986), reports that J-13 was pumped nearly continuously (at an unspecified rate) for many years during which time decreases in the static water level were less than 1 m.

The final interpretations in this section are drawn from the numerical modeling results of Czarnecki (1991). Maximum water level declines of about 10 feet (3 m) were simulated for "an extreme case" of pumping at 1,390 gallons per minute (5,300 liters per minute) for 10 years. Whether this represents an extreme case depends on the water requirements for the repository and other activities in Jackass Flats, requirements that are not quantified in the TBR. As noted previously, the model simulation results are a function of numerous model assumptions and parameter estimates that are not discussed or evaluated in the TBR.

Credible Alternative Interpretations

The interpretations that would be most sensitive to alternative hypotheses are those related to the numerical simulation results of Czarnecki (1991). These results are based on a particular conceptual model of the hydrogeologic system, described by Czarnecki (1985), which assumes that a steep gradient to the north of the site results from a zone of low permeability. Several other conceptual models have been proposed to explain the high-gradient area, but none of these are described in the TBR. They include a model in which a high-permeability zone acts as a drain to connect the tuff aquifer to the underlying carbonate aquifer (Fridrich et al., 1994) and another model in which the anomalously high water levels north of the proposed repository correspond to perched conditions (Ervin et al., 1994). The TBR does not discuss if and how acceptance of any of the alternate conceptual models might affect predictions of drawdowns and sustainability of ground water supplies during repository construction and operation.

The TBR also does not consider the effects of other water demands in the region (e.g., for irrigation) on the availability of ground water for the repository. Extensive pumping in adjacent basins could have significant effects on water levels in the vicinity of Yucca Mountain, particularly if these rates represent a significant portion of the regional discharge. For example, La Camera and Westenburg (1994) estimate that production rates in the Amargosa Desert during 1985-1992 were 20 to 60 times higher than those in Jackass Flats. The maximum estimated production rates cited by La Camera and Westenburg (1994) in the Amargosa Desert [more than 3 x 10^9 gallons per year (1 x 10^{10} liters per year)] are very similar to the estimate of total steady-state discharge in Franklin Lake Playa used in the model by Czarnecki and Wadell (1984), which constitutes more than 60 percent of the estimated steady-state discharge in the region.

Testing to Discriminate Among Alternative Interpretations

If the particular values of drawdown predicted by Czarnecki (1991) are critical to regulatory compliance, DOE will need to refine its understanding of the apparent high-gradient zone through field testing. Appropriate tests would include drilling holes in the high-gradient area for evaluation of lithologic and hydrologic properties. To test the perched water hypothesis, water level measurements and hydraulic tests (pumping, slug, injection, tracer) in multiple holes completed to different depths, or a series of packer tests in a single hole, could yield useful information on vertical gradients and lateral continuity of possible perched intervals. To test the drain model, multiple wells extending into the carbonate aquifer below the tuff would be required.

Conceptual and numerical models of the ground water system would benefit from additional measurements of water levels and aquifer properties throughout the region. New estimates of transmissivity could be obtained from analysis of tests in recently completed boreholes in Midway Valley (Geldon, 1993). Additional data that would be useful to an assessment of competing future demands for ground water would be production histories and projected future pumping rates of wells in nearby areas such as the Amargosa Desert.

Alternatively, if bounding estimates of drawdown are all that are required for regulatory purposes, it may be acceptable to perform a sensitivity study by constructing numerical models consistent with the alternative hypotheses for the high-gradient zone and comparing drawdowns predicted by these models to those of Czarnecki (1991). A simplified analytical approach, evaluating whether drawdowns under alternative conceptual models will be greater than those of Czarnecki (1991), could also suffice.

Drilling of additional holes and field testing are likely to yield the most useful information on the hydrologic system that could help resolve questions related to the nature of the high-gradient area to the north of the proposed repository. For the purposes of bounding the availability of ground water supplies for construction, however, this may not be necessary, as discussed below.

Summary and Conclusions

The water supply section of the TBR presents interpretations related to ground water availability, with emphasis on historic pumping rates and on drawdowns predicted by using a numerical model. It provides few data to support these interpretations and does not consider alternative conceptual models of the ground water system that may affect model predictions. The most serious deficiency of the discussion of preclosure water supply issues in the TBR is the lack of a clear statement of the technical questions that must be answered to establish the sufficiency of the water supply for repository construction and operation. The technical questions could be framed in terms of absolute availability of water or in terms of a bounding calculation. If DOE chooses to attempt to quantify the absolute availability of ground water in the Jackass Flats area, testing and comparison of alternative models would be required. The lack of data and constraints for ground water flow models throughout the basin, but particularly in the area of apparent high gradient in the water table north of Yucca Mountain, would be significant limitations to answering this technical question.

It is likely that the regulatory requirements could be satisfied by answering a technical question framed in terms of bounding calculations. A three-step approach that could be taken to address a technical question of this form is outlined below:

1. Determine a reasonable upper-bound estimate of water requirements for repository construction and operation, including peak annual usage and duration. The technical question to be addressed is whether existing water supply wells in the tuff aquifer can supply water at this rate for the specified duration, when other concurrent demands are also considered.

2. Compare historic production rates and the observed drawdowns in existing wells and nearby monitoring wells to the required pumping rates for the bounding estimate of water supply needed for the repository. This comparison may indicate directly

that existing wells have produced water, without excessive drawdowns, at similar rates and for similar durations to those required for the repository. If this is the case, the technical question may be answered without numerical modeling of the system.

3. If the comparison of historic pumping rates to an upper-bound estimate of water requirements does not yield a clear answer to the technical question, numerical models could be employed. If such models are used to address the technical question of water availability, a discussion of model assumptions and calibration data must be included. The possible changes in predicted water level declines that would result from incorporating alternative conceptual models into the simulations would have to be assessed in this case. Especially important to this analysis would be a comparison of results generated by numerical models incorporating the alternative conceptual models that have been proposed to account for the high-gradient area north of the proposed repository.

4
CONCLUDING COMMENTS

The previous chapters in this report have provided a detailed review of the scientific and technical information in the technical basis report (TBR) related to surface characteristics, erosion, and preclosure hydrology. In this final chapter of its review, the committee wishes to address a broader question: How effective is the TBR at meeting its stated objective as " . . . a synthesis of currently available site characterization data, analyses, and technical interpretations . . ." (TBR, Preface, p. v)?

In addressing the question of effectiveness, it is important to consider the context for the TBR. This TBR is the product of an effort of great national importance: to assess the suitability of Yucca Mountain as a facility for the safe permanent disposal of high-level radioactive waste. For this effort to succeed, the Department of Energy (DOE) will need to demonstrate that it has a good understanding of the scientific and technical issues that would affect the construction and long-term performance of such a facility. Given the importance of this undertaking to the health and safety of present and future generations of this nation's citizens, it is this committee's opinion that the scientific and technical analyses presented in the TBR should meet the highest standards of scientific quality. Considered in this context, it is the committee's judgment that this TBR is not an effective synthesis of data, analyses, and interpretations related to surface characteristics, erosion, and preclosure hydrology. The following sections provide the committee's reasons for this conclusion. In the spirit of peer review as a method to improve scientific quality, these sections also offer constructive suggestions of ways to increase the effectiveness of this and future TBRs.

AUDIENCE FOR THE TBR

The audience for this TBR is never defined clearly in the report. During the course of this review, particularly during the public information-gathering sessions, it became clear to the committee that a number of different audiences were interested in this TBR. Foremost among these interested parties are regulators and policymakers who will be responsible for ultimately licensing and providing funds for the construction and operation of the proposed repository; the scientific community, whose members are knowledgeable or concerned about the issues addressed in this TBR; and the public, particularly the state and local institutions and individuals potentially affected by the decision to site a facility at Yucca Mountain.

In the committee's judgment, the TBR is not written effectively for any of these audiences for a variety of reasons, many of which are noted in the previous chapters: The technical questions addressed in each of the sections of the TBR are not stated clearly; the presentation of data and analyses is incomplete; and the lack of effective graphics makes for difficult reading and comprehension. The report is to a significant extent inaccessible to nonscientific readers.

In the committee's opinion, the credibility of the TBR and the underlying site characterization program would be increased if the report were written to be comprehensible to a broad audience. The committee recognizes the significant challenges involved in producing a report that is broadly comprehensible–particularly when that report is highly technical in nature and contains extensive technical documentation. The committee believes, however, that it is possible to produce such a document by utilizing a variety of stylistic devices. These include the use of additional graphics (e.g., detailed maps and cross sections) to illustrate technical points, the use of appendixes for technical documentation, and the use of extended, "nontechnical" summaries for managers, legislators, and the public.

Recommendation: The audiences for the TBR should be stated explicitly in the report, and the TBR should be written to be comprehensible by these groups. The designation of target audiences is a DOE policy issue. The committee recommends that DOE policymakers carefully consider the advantages of writing for a broad audience to build scientific credibility and public acceptance for its site characterization program.

QUESTIONS ADDRESSED BY THE TBR

The scientific and technical questions to be addressed by the TBR also were not stated clearly in the report. The TBR does provide the qualifying and disqualifying conditions from 10 CFR

960[1] relevant to surface characteristics, erosion, and preclosure hydrology—but there is little attempt to discuss the associated technical questions that need to be answered or hypotheses that need to be tested in order to assess compliance with these 10 CFR 960 conditions.

The concern here is not whether the TBR demonstrates compliance with 10 CFR 960. Indeed, consideration of compliance issues is outside the committee's statement of task (Appendix C). Rather, the concern is the context in which the scientific and technical content of the TBR is to be assessed. Without a clear statement of the questions to be addressed, the report reads as more of a narrative rather than a focused technical analysis. A list of questions or hypotheses of concern at the beginning of each major section of the TBR would have served to focus the supporting technical analysis—and would have made it easier for the committee and other concerned readers to assess whether that technical analysis adequately addressed those questions.

The committee's review of water resource potential (Chapter 3 of this report) perhaps best illustrates the problem with assessing technical analysis in the absence of a clear problem statement. It was unclear to the committee whether the point of the analysis was to determine (1) total available water supply or (2) some minimum, or bounding, estimate of supply. The differences between these points may seem to be minor, but they are significant for assessing whether the supporting technical analyses are adequate. The committee has provided examples of the kinds of focus questions that should have appeared in the TBR in Chapters 2 and 3 of this review.

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1 Title 10, Part 960 of the Code of Federal Regulations, General Guidelines for the Recommendation of Sites for Nuclear Waste Repositories.

Recommendation: The TBR should contain a clear statement of the questions to be addressed and hypotheses to be tested for each technical topic. These questions will serve to focus the supporting technical analyses and make it easier for the reader to assess their adequacy.

SYNTHESIS OF AVAILABLE DATA

Another problem noted by the committee in its review is the failure of the TBR to explicitly address all available data in the scientific and technical analyses. This problem may not be apparent to nonexpert readers without knowledge of the scientific literature related to the site characterization program. However, this deficiency was recognized by scientists and other technically oriented individuals identified by DOE as "stakeholders" in the site characterization process, and a number of these individuals pointed out this problem to the committee during its information-gathering sessions. This deficiency also became very clear to the committee during its review of the scientific literature cited in the TBR and made it difficult for the committee to perform its review.

There are two aspects of the data synthesis issue that deserve comment. The first is a failure to reference and discuss all data relevant to the issues addressed by the TBR, as noted elsewhere in this review. For example, Chapter 2 of the TBR does not synthesize the surficial work done by DOE and its contractors on Jackass Flats (Lundstrom et al., 1995), nor does it cite or discuss the surficial work done by State of Nevada scientists on Crater Flat (Faulds et al., 1994)—even though these results are generally consistent. The committee believes that incorporation of the Crater

Flat work into the TBR would have provided a more complete understanding of the surficial geology of the Yucca Mountain region. The failure of the TBR to explicitly address all available data calls into question the thoroughness with which the scientific and technical issues were evaluated.

The second aspect of the data synthesis problem relates to tracing information used in the TBR back to primary references. Many of the data and models cited in the TBR were taken from previously published papers, and references to those papers are provided throughout the report. However, in some cases, the committee found it difficult to trace information and conclusions cited in the TBR back to those references. For instance, as noted in the review of surface flooding (Chapter 3 of this report), the TBR incorporates technical information from three published papers (Bullard, 1991; Blanton, 1992; Glancy, 1994) to estimate probable maximum flooding (PMF). However, it is not clear from the discussion in the TBR how the information from these three sources was used to make the PMF estimates; nor are reasons given for the selection of parameter values used in the analyses. Similarly, the TBR does not provide details of the model used by Czarnecki (1991) to estimate the effects of ground water withdrawals. The TBR cites an earlier paper by Czarnecki (1985) as the source of details on this model, but in fact, much of the basis for the model is not found in that paper but in Waddell (1982) and Czarnecki and Waddell (1984).

The ability to trace information back to primary sources is important for two reasons: (1) it allows readers to access related background and explanatory information to increase understanding; and (2) it also allows them to check that the information from these sources has been used correctly. The ability to trace information back to primary references is one of many essential requirements for establishing the scientific credibility of any scientific or technical document.

Recommendation: All available scientific and technical information related to the issues addressed in the TBR should be cited and discussed. In addition, essential information (e.g., data, equations, and model parameters) used in analyses should be provided in the TBR, and primary sources should be referenced.

SYNTHESIS OF ANALYSES

In the committee's judgment, the TBR does an inadequate job of compiling and synthesizing available data and analyses to explain the scientific and technical issues related to surface characteristics, erosion, and preclosure hydrology. Indeed, the TBR presents the results of analyses with relatively little synthesis or documentation. As a consequence, it was difficult and in some cases impossible for the committee to check these analyses. Nor was it always possible to determine whether alternative analyses had been attempted and, if so, to assess the results of those efforts.

The TBR could be improved significantly by including a more complete discussion of analyses supporting the technical interpretations; a discussion of alternative hypotheses and the methods used to test them; and a discussion of remaining uncertainties and additional data needed to address them. The TBR is a scientific and technical document and should follow conventional practice with respect to presentation of data, testing of hypotheses, and acknowledgment of uncertainties.

Recommendation: The TBR should provide a complete discussion of analyses supporting the technical interpretations; a discussion of alternative hypotheses and the methods used to test them; and a discussion of remaining uncertainties and additional data needed to address them.

During its first information-gathering session, the committee learned that the TBR was compiled by a single individual who was working under extremely tight deadlines. The committee understands that this person was broadly knowledgeable about Yucca Mountain and site characterization efforts, but was not involved directly in the scientific studies addressed in the TBR. These criticisms are not directed at the individual who compiled the TBR, but rather at the management process that led to preparation of the TBR by someone other than the scientists whose work was used in the report.

The integration of data and analyses from multiple sources into a coherent document is a complex and difficult process. The committee believes that this process is carried out most effectively with the direct involvement of those doing the science—in this case the scientists who are involved directly in site characterization efforts—because they have the most complete understanding of the data and methodologies and are trained in analytical synthesis. In order to assess the quality of this integration, it is also necessary to understand how the integration was carried out and to know who was involved in the process.

> **Recommendation:** The TBR should be prepared with the direct involvement of the scientists who did the site characterization studies, and these scientists should be identified in the report. The TBR should also provide a discussion of how data and analyses were selected and integrated.

A recurring theme in the committee's detailed review of the TBR (Chapters 2 and 3 of this report) is the importance of using multiple techniques of analysis to improve understanding, reduce uncertainties, and thereby build confidence in the interpretations and conclusions. Multiple-methodology approaches seem particularly well suited to many of the problems addressed in the TBR. As noted in Chapter 2 of this report, for example, the use of multiple geochronologic methods for measuring surface exposure ages might have significantly reduced uncertainties and increased confidence in the validity of the results obtained from the cation ratio dating method. Similarly, the use of multiple techniques to estimate rates of erosion would have provided information on the spatial distribution of rates at Yucca Mountain and could have generated more reasonable ranges of estimates in the vicinity of the proposed repository.

A valuable tool in the arsenal of multiple methodologies is the bounding calculation, which can be used to determine minimum or maximum values of processes or phenomena. Bounding calculations could have been used to address many of the questions in the TBR with little or no additional data collection. As noted in Chapter 3 of this report, for instance, such calculations could probably have been used to demonstrate that there is an adequate supply of water for construction and operation of the proposed repository. Other examples of bounding calculations are given in the summary and conclusions section on erosion in Chapter 2.

In the committee's judgment, the TBR placed too much emphasis on producing single numbers that could be compared to some specified standard, perhaps to demonstrate regulatory compliance. The effort to produce a single estimate of erosion (Chapter 4 of the TBR) for the Yucca Mountain region is perhaps the best example of this tendency. Science is a process of logical inquiry into the nature of the world. The committee believes that the management of science is not achieved most effectively when the results of such inquiry (e.g., geochronological measurements in laboratories and field measurements of processes) are generated in separate investigations, transformed into numerical form, and subsequently combined by formula to yield a prediction (e.g., of erosion rate) that is envisioned primarily for comparison to a regulatory standard.

The committee's concern with this approach is threefold: (1) there is little room for formulating or testing alternative hypotheses of processes and applying multiple methodologies; (2) there is little opportunity to assess the "hidden" uncertainties that exist because all processes are not measured; and (3) the spatial and temporal variabilities in rates and processes are obscured through the use of average values. The focus on generating average values or single explanations is contrary to science as an open process of inquiry in which investigators are encouraged to invent alternative explanations for phenomena, explore the whole range of natural causative processes, and make discoveries of previously unrecognized facts—even if those facts seem inconsistent with current theories.

The types and numbers of analyses presented in this TBR appear to reflect, to a great extent, decisions made by DOE on the kinds of studies to undertake during the site characterization phase of its program. It is beyond the charge of this committee to comment on those decisions specifically or to evaluate DOE's site characterization program. However, it appears that the failure of the TBR to employ multiple methodologies may be traced to management decisions that discouraged the use of such methodologies in an iterative and integrative manner as site characterization progressed.

Recommendation: Multiple methods of analysis should be employed in the TBR to improve understanding, reduce uncertainties, and thereby build confidence in its interpretations and conclusions. Bounding calculations are particularly well suited to many of the issues addressed in the TBR and should be applied as part of a multiple-methodology approach to place minimum or maximum bounds on processes and phenomena.

PRESENTATION OF DATA AND ANALYSES

Aside from the fact that necessary data are not always provided in the TBR, as noted previously, the data, analyses, and conclusions generally are not presented effectively. Of particular concern to the committee is the absence of basic geologic and topographic maps and cross sections to orient the reader and to illustrate spatial relationships among the various elements of the site: the land surface, surface drainages, rock units, surficial deposits, the proposed repository, the ground water table, perched water zones, and important data collection sites. Many of the graphics used in the TBR are inadequate; they lack even rudimentary information such as accurate topography and scale. The lack of informative graphics and tables makes the report less understandable to readers and, therefore, discourages readers from developing their own understanding of the underlying scientific and technical issues.

The committee also discovered several minor, yet nagging, production-related errors in its review of the TBR. For example, Section 4.5 in the report is missing—most likely an error in the table of contents; there are citation errors (e.g., Figure 3.3-4 is from Czarnecki, 1991, not 1992 as given in the figure caption); pages 3.6 and 3.5 are reversed; and there are simple mistakes of fact. Such errors detract from the readability of the TBR and inevitably call into question the thoroughness with which it was reviewed before its release.

Recommendation: The TBR should be illustrated with informative graphics to orient the reader to the region and to illustrate spatial relationships among the various elements of the site. Of particular importance are geologic and topographic maps and cross sections that illustrate the locations of land surfaces, drainages, rock units, surficial deposits, perched and ground water, the proposed repository, and selected data collection sites.

PEER REVIEW

Many of the problems noted in this report could have been discovered and corrected had an effective peer review mechanism been in place during preparation of the TBR. The committee learned during its first information-gathering session that the scientists working in the site characterization program—whose data and analyses are cited in the TBR—had an inadequate opportunity to review the TBR before it was released. During its information-gathering sessions, the committee also observed an apparent lack of communication and research integration among scientists involved in site characterization and between project scientists and other researchers, not supported by the DOE, who are working in related areas.

Peer review is an integral part of science, and such review is most effective when it is integrated throughout the scientific process—starting with decisions on what problems to address and how to address them; as a check on the quality of the investigations themselves; and finally, as a check on the quality of the presentation of results. The DOE has demonstrated its commitment to peer review at several steps in the site characterization process—for example, in its quality assurance program to ensure that the scientific and engineering data used in site characterization efforts are of high quality, and in its commitment to obtaining external peer review of the TBRs as demonstrated by the work of this committee. Yet quality cannot just be added on at the end of a project; it has to be built in to every step of the process.

The committee also learned at its first information-gathering session that the issue of erosion had been reviewed by the U.S. Nuclear Regulatory Commission (USNRC, 1994) prior to the release of this TBR. There is no reference made to this review in the TBR; nor does the TBR address the issues raised in the USNRC review related to extreme erosion and the cation ratio dating method. To be useful, peer review must have an influence on the scientific process; that is, peer review must be allowed to feed back into scientific investigations. There is no indication that such feedback occurred in the preparation of this TBR.

Recommendation: Preparation of the TBR should include provision for a rigorous program of peer review by scientists whose work is used in the report. This should occur in addition to external peer review, which serves as an independent check on scientific and technical quality. The peer review process should also include provisions to ensure that the results of internal and external peer review effectively feed back into this and future TBRs and, when appropriate, into the associated scientific and technical programs.

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APPENDIX A

LIST OF ACRONYMS AND SYMBOLS

CRD	Cation ratio dating
DOE	U.S. Department of Energy (also USDOE)
DTM	Digital topographic model
ESF	Exploratory Studies Facility
M	Process magnitude, from Equation 2.3
n	Manning hydraulic resistance coefficient (see Chapter 3, footnote 5).
NAS–NRC	National Academy of Sciences–National Research Council
OCRWM	Office of Civilian Radioactive Waste Management
PMF	Probable maximum flood
PMP	Probable maximum precipitation
R	Process rate, from Equation 2.3
RAT	Reasonably available technology
T	Time of process operation, from Equation 2.3
TBR	U.S. Department of Energy *Technical Basis Report for Surface Characteristics, Preclosure Hydrology, and Erosion*
USEPA	U.S. Environmental Protection Agency
USNRC	U.S. Nuclear Regulatory Commission
YMSCO	Yucca Mountain Site Characterization Office

APPENDIX B

BIOGRAPHICAL SKETCHES OF COMMITTEE MEMBERS

SMERDON, Ernest T., *Chairman*—Dr. Smerdon is professor of civil engineering, professor of hydrology and water resources, and vice provost and dean of the College of Engineering and Mines at the University of Arizona. His research interests include water policy issues, water use in irrigation, mechanics of water erosion and sediment transport, irrigation hydraulics, soil-water-plant relations and water control, and energy conservation and use in food production. He earned his M.S. and Ph.D. in agricultural and civil engineering from the University of Missouri. Dr. Smerdon is a member of the National Academy of Engineering, an honorary member of the American Society of Civil Engineers, and fellow of both the American Society of Agricultural Engineers and the American Association for the Advancement of Science. Dr. Smerdon is a member of the Governor's Science and Technology Council in Arizona. He is a recipient of the Engineer of the Year Award of the Arizona Society of Professional Engineers.

BAHR, Jean M., *Vice Chair*—Dr. Bahr is an associate professor in the Department of Geology and Geophysics and the Institute for Environmental Studies at the University of Wisconsin, Madison. She is also chair of the Water Resources Management Program and a member of the Geological Engineering Program faculty. Her research interests include ground water hydrology, ground water geochemistry, and surface water-ground water interactions. She earned her M.S. and Ph.D. degrees in applied earth sciences from Stanford University. Dr. Bahr is a member of the editorial boards of *Geotimes* and *Ground Water* and is a member of the National Research Council's Board on Radioactive Waste Management.

BAKER, Victor R.—Dr. Baker is a professor of geosciences, professor of planetary sciences at the Lunar & Planetary Laboratory, and Regents Professor of the Department of Geosciences and the Department of Planetary Sciences at the University of Arizona, Tucson. His research interests include geomorphology; fluvial geomorphological studies in the western United States, Australia, India, Israel, and South America; flood geomorphology; paleohydrology; Quaternary geology; natural hazards; geology of Mars and Venus; and philosophy of earth and planetary sciences. He received his Ph.D. in geology from the University of Colorado. Dr. Baker is a fellow of the Geological Society of America and the American Association for the Advancement of Science.

BRANTLEY, Susan L.—Dr. Brantley is an associate professor of geosciences at Pennsylvania State University. Her research interests include thermodynamics and kinetics of rock-water interaction over the temperature range 25 to 600 °C, dissolution and precipitation reactions of minerals, natural brines, mineral surface chemistry, and alteration of porosity and permeability. She received her B.A. in chemistry, and her M.A. and Ph.D. in geological and geophysical sciences from Princeton University. Dr. Brantley is a recipient of a National Science Foundation Presidential Young Investigator Award.

JURY, William A.—Dr. Jury is professor of soil physics in the Department of Soil and Environmental Sciences at the University of California, Riverside. His principal research interests include measurement and modeling of organic and inorganic chemical movement and reactions in field soils, development and testing of organic chemical screening models, and characterization of the spatial variability of soil physical and chemical properties. He received his M.S. and Ph.D. degrees in physics from the University of Wisconsin. Dr. Jury is a fellow of the American Association for the Advancement of Science and the Soil Science Society of America. In 1989 he received the National Soil Science

Research Award of the Soil Science Society. He is also the recipient of the National Environmental Quality Research Award of the Agronomy Society of America.

KURZ, Mark D.—Dr. Kurz is an associate scientist and supervisor of the Isotope Geochemistry Facility at the Woods Hole Oceanographic Institution. His research interests include isotope geochemistry of mantle-derived rocks and minerals and their use to constrain the origin of mantle heterogeneity; the use of noble gas isotopes to understand the degassing history of the earth; and the production and distribution of cosmic-ray-generated nuclides in surficial rocks and their application to exposure dating of Quaternary surfaces, particularly in reconstructing the history of the Antarctic ice sheets. He received his Ph.D. in geochemistry from the Joint Program in Oceanography administered by the Massachusetts Institute of Technology and Woods Hole Oceanographic Institution. Dr. Kurz is a recipient of the Ruth and Paul Fye Award for Excellence in Oceanographic Research from Woods Hole Oceanographic Institution; the F.W. Clarke Medal of the Geochemical Society; and the Rosenstiel Award for Outstanding Achievement in Oceanographic Science from the University of Miami.

LANE, Leonard J.—Dr. Lane is a supervisory research hydrologist for the U.S. Department of Agriculture and the Current Research Information System (CRIS) project leader. His research interests are in the areas of hydrology, hydrologic modeling, erosion and sedimentation, contaminant transport processes, waste management, global change, and decision support systems. He earned his M.S. from the University of Arizona and his Ph.D. in civil engineering, hydrology, and water resources from Colorado State University. Dr. Lane is the recipient of the Mountain States Area Scientist of the Year Award and the U.S. Department of Agriculture Superior Service Team Award.

PRESTEGAARD, Karen L.—Dr. Prestegaard is an associate professor of geology at the University of Maryland. Her primary research interests include fluvial geomorphology, sediment transport, mechanics, field studies of watershed hydrologic and solute flux processes, and wetland hydrology. She received her M.S. and Ph.D. degrees in geology from the University of California, Berkeley. She has served as councilor and in other capacities for the Geological Society of America and has held offices in the Hydrology Section of the American Geophysical Union. Dr. Prestegaard is a fellow of the Geological Society of America.

APPENDIX C

STATEMENT OF TASK

The committee will perform a scientific and technical review of the April 1995 Yucca Mountain Site Characterization Project *Technical Basis Report for Surface Characteristics, Preclosure Hydrology, and Erosion.*

The committee will evaluate this report to assess the validity of the data and interpretations and the adequacy of the treatment of uncertainties in describing the current state of understanding. The committee will review only the technical and scientific analyses. The committee will not address regulatory compliance, nor will it address the suitability of the Yucca Mountain site as a high-level radioactive waste repository. The committee will prepare a written report of its findings for distribution to OCRWM and interested members of the public.

The review will address (but will not be limited to) the following questions:

a. Have the data been collected and analyzed in a technically acceptable manner?
b. Do the data, given the associated error and analytical and technical uncertainties, support the technical interpretations and conclusions made within the technical basis report?
c. Are there credible alternative interpretations that would significantly alter the conclusions reached?
d. What testing, if any, would discriminate among alternative technical interpretations?
e. If such testing is recommended, how effective would it be at reducing significant uncertainties?

The committee will attempt to distinguish between recommendations for further technical work to reduce uncertainty, and any recommendations pertaining to DOE policy or management.

APPENDIX D

LIST OF LIAISONS

William D. Barnard
U.S. Nuclear Waste Technical Review Board

Dennis A. Bechtel
Clark County, Nevada

Michael Bell
USNRC

Les W. Bradshaw
Nye County, Nevada

Ray Clark
USEPA

Al Colli
USEPA

Robert W. Craig
U.S. Geological Survey

A.C. Douglas
City of Las Vegas, Nevada

Margaret Federline
USNRC

Sandi Green
Eureka County, Nevada

Juanita D. Hoffman
Esmeralda County, Nevada

Carl Johnson
Nevada Nuclear Waste Project Office

Robert R. Loux
Nevada Nuclear Waste Project Office

Tammy Manzini
Lander County, Nevada

Florindo Mariani
White Pine County, Nevada

Brad R. Mettam
Inyo County, California

Calvin Meyers
Moapa Band of Paiutes

Jason Pitts
Lincoln County, Nevada

Vernon E. Poe
Mineral County, Nevada

Jonathan G. Price
Nevada Bureau of Mines and Geology

James Regan
Churchill County, Nevada

Leon Reiter
U.S. Nuclear Waste Technical Review Board

Harold A. Rogers
The Study Committee, Nevada

Jane Summerson
USDOE, OCRWM

Judy Treichel
Nevada Nuclear Waste Task Force, Inc.

Engelbrecht von Tiesenhausen
Clark County, Nevada

APPENDIX E

OPEN MEETING AGENDAS

AGENDA: MEETING 1

Committee for Yucca Mountain Peer Review:
Surface Characteristics, Preclosure Hydrology, and Erosion

Holiday Inn Crowne Plaza
4255 South Paradise Road
Las Vegas, Nevada 89109

July 19-20, 1995

Wednesday, July 19, 1995

OPEN SESSION

8:30-8:45 a.m.	**Welcome and Introductions** *Ernest T. Smerdon, Chair* *Kevin D. Crowley, Study Director* • Purpose and plan for the meeting • Introduction of committee and staff
8:45-9:30 a.m.	**Project Background; National Academy of Sciences Procedures and Policies** *Ernest T. Smerdon, Chair* *Kevin D. Crowley, Study Director*

	• Charge to the committee • Review of the NAS–NRC study process • General operating procedures for this project • Project schedule • Policies regarding public access and confidentiality • Policies regarding audio and video recording • Policies regarding public input
9:30-10:30 a.m.	**Development of Technical Basis Reports and the Committee's Task** *Jane Summerson, DOE–YMSCO*
10:30-11:00 a.m.	**BREAK**
11:00-11:45 a.m.	**U.S. Nuclear Regulatory Commission Perspectives on the Technical Basis Report** *Mike Bell, USNRC*
11:45 a.m.-12:00 p.m.	**Questions and Discussion** *Committee and Presenters*
12:00-1:30 p.m.	**LUNCH**
1:30-2:00 p.m.	**State of Nevada Perspectives on the Technical Basis Report** *Carl Johnson, Nevada Nuclear Waste Project Office*
2:00-2:30 p.m.	**Public Trust and the Nuclear Waste Program** *Judy Treichel, Nevada Nuclear Waste Task Force, Inc.*

2:30-3:30 p.m.	**Presentations by Other Affected Units of Government**
3:30-4:00 p.m.	**BREAK**
4:00-5:30 p.m.	**Opportunity for Public Comment**

Thursday, July 20, 1995

OPEN SESSION

8:30-8:40 a.m.	**Summary of Yesterday's Activities and Plan for the Day** *Ernest T. Smerdon, Chair*
8:40-9:30 a.m.	**U.S. Geological Survey Perspectives on the Technical Basis Report** *John Stuckless, Yucca Mountain Project Branch, USGS*
9:30-9:45 a.m.	**Nuclear Waste Technical Review Board Perspectives on the Technical Basis Report** *Leon Reiter, NWTRB*
9:45-10:15 a.m.	**Discussion** *Committee and Presenters*
10:15-10:45 a.m.	**BREAK**
10:45 a.m.-12:00 p.m.	**Additional Presentations by Affected Units of Government and Opportunity for Public Comment**
12:00-1:30 p.m.	**LUNCH**

1:30-2:15 p.m.	**Preliminary Discussion of Schedule and Assignments** *Committee*
2:15-3:00 p.m.	**Preliminary Discussion of Plans for the Next Meeting, Including Field Trip** *Committee*
3:00-3:30 p.m.	**BREAK**
3:30-5:00 p.m.	**Opportunity for Public Comment**

AGENDA: MEETING 2

Committee for Yucca Mountain Peer Review:
Surface Characteristics, Preclosure Hydrology, and Erosion

Beatty, Nevada
Yucca Mountain Site

August 27-29, 1995

Sunday, August 27, 1995

7:00 a.m.	Field trip participants will depart for Beatty from the La Quinta Inn, Las Vegas.
8:30 a.m.	Rendezvous at Lathrop Wells (Amargosa Valley), intersection of Routes 95 and 29, for introductions of committee and visitors and a brief review of the purpose and plan for the field trip.
	Stop 1: U.S. Route 95 at Fortymile Wash. Erosional history of Fortymile Wash and historical flooding [DOE: Whitney, Lundstrom, and Beck; State: Mifflin]. One hour.
	Stop 2: Lathrop Wells Cone. Comparison of dating techniques; techniques to infer erosion [DOE: Crowe]. One hour.
12:00 p.m.	Arrive at Beatty, Nevada.
2:00-6:00 p.m.	**Open Session at Beatty Community Center**

2:00-4:00 p.m.	**Committee Discussion on Hydrology.** The committee will ask questions of DOE scientists on the following topics:
	Perched water. Nature, extent, occurrence, and flux rates; dating and other geochemical work; experimental design to find perched water; how well perched water is understood and can be predicted. [DOE: Luckey and Czarnecki; State: Mifflin]
	Ground water supply. Given alternative conceptual models for steep hydrologic gradients north of Yucca Mountain, how do they affect predictions of ground water drawdown. [DOE: Luckey and Czarnecki; State: Mifflin]
	Probable Maximum Flooding. Details of calculations to determine probable maximum flood boundaries. [DOE: Barton]
4:00-6:00 p.m.	**Committee Discussion and Public Comment**

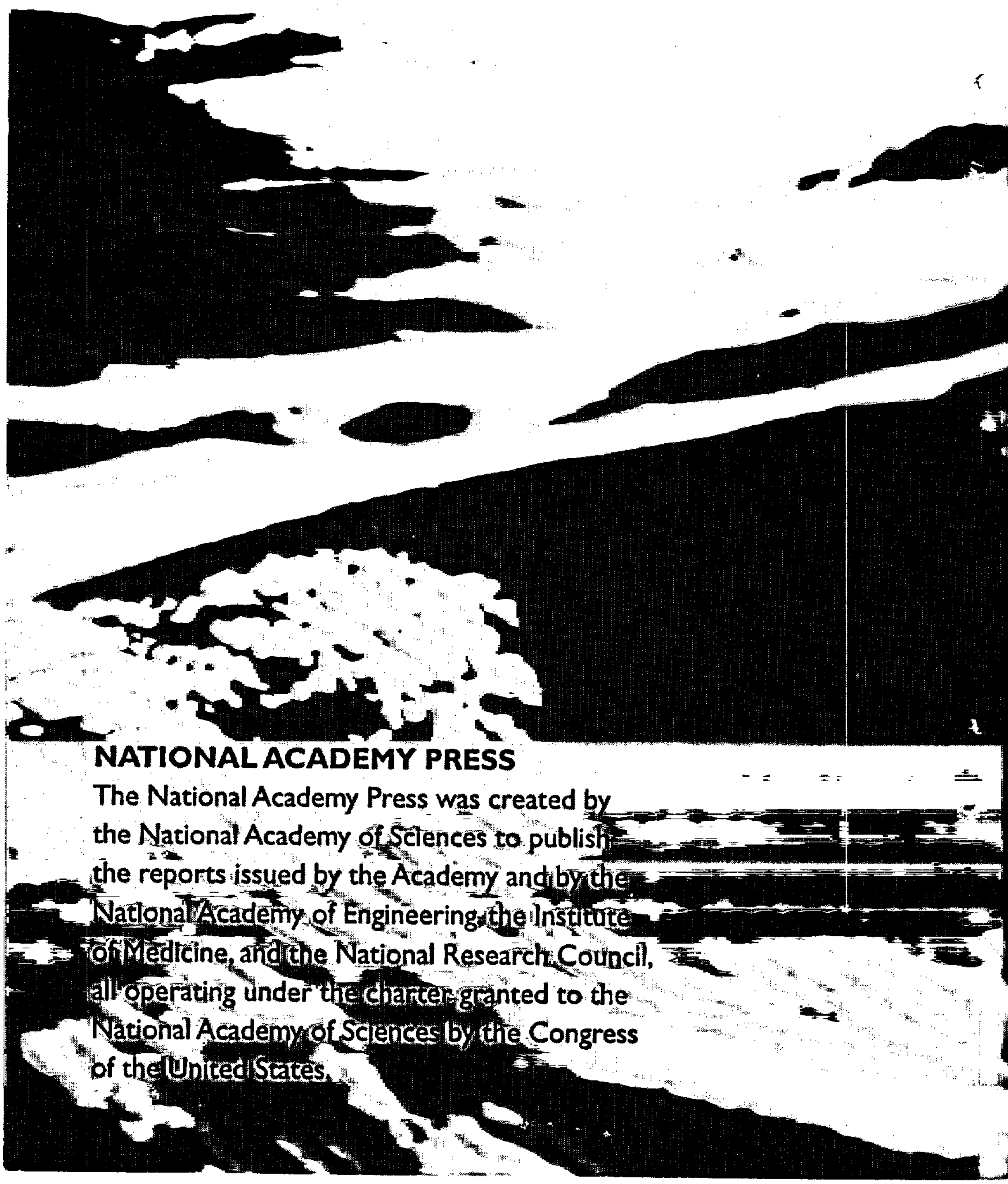
Monday, August 28, 1995

6:00 a.m.	Depart Beatty to Nevada Test Site Gate 510 for badging.
6:30 a.m.	Rendezvous at Gate 510 for badging.
7:00 a.m.	Depart Nevada Test Site Gate 510.

8:00-11:00 a.m.	**Stop 3: Big Skull Mountain Vista.** Erosional history, debris flows, and varnish dating. [DOE: Whitney and Harrington; State: Dorn]
	Stop 4: LSM-1 Boulder Deposit. Erosional history, debris flows, and varnish dating. [DOE: Whitney and Harrington; State: Dorn]
11:00 a.m.-12:00 p.m.	**LUNCH** (Site Characterization Office)
12:00-3:00 p.m.	**Stop 5: Fortymile Wash Vista.** Drainage evolution, incision rates, and Quaternary history. Geochronologic studies of surficial deposits at Yucca Mountain. [DOE: Whitney, Lundstrom, and Paces; State: Spaulding]
	Stop 6: Jake Ridge. Debris flows from a storm event. [DOE: Whitney]
3:00-4:00 p.m.	**Stop 7: Trench 14D/Crest Exile Hill.** Surficial deposits and alluvium/colluvium relationships as evidence for erosion rates. Amounts of Quaternary faulting related to enhanced erosion. [DOE: Lundstrom, Whitney, and Paces; State: Bell]
4:00-5:30 p.m.	**Stop 8: Yucca Crest.** Wrap-up and overview of tomorrow's work. [DOE: Whitney and Harrington]
5:30 p.m.	Depart for Beatty via Test Site Gate 510.

Tuesday, August 29, 1995

6:00 a.m.	Committee will depart from Beatty.
6:45 a.m.	Rendezvous at Steves Pass turnaround.
6:45 a.m.	**Stop 9: Steves Pass.** Overview of Crater Flats, including geomorphology and soils. [DOE: Whitney; State: Bell, Spaulding]
	Stop 10: Crater Flats Cinder Cone. Erosional history. [DOE: Harrington; State: Bell, Spaulding]
	Stop 11: Trench 8. Boulder deposits, relationship of colluvium with hillslope deposits, erosion rates, and antiquity of colluvial deposits as determined from K-horizon carbonates. [DOE: Whitney, Harrington, and Paces; State: Bell]
	Stop 12: SCFT-3. Boulder deposits, relationship of colluvium with hillslope deposits, erosion rates, and antiquity of colluvial deposits as determined from K-horizon carbonates. [DOE: Whitney, Harrington, and Paces; State: Bell]
	Technical wrap-up (Whitney); next steps and schedule (Smerdon); comments by committee members and other participants.
12:00 p.m.	Depart for Las Vegas.



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