OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT

1. QA: QA

ANALYSIS/MODEL COVER SHEET

COMPLETE ONLY APPLICABLE ITEMS

2. ☒ Analysis — Check all that apply

Type of Analysis	☐ Engineering ☐ Performance Assessment ☒ Scientific
Intended Use of Analysis	☐ Input to Calculation ☒ Input to another Analysis or Model ☐ Input to Technical Document ☐ Input to Other Technical Products
Describe use: Use of geochemical and isotopic data to estimate groundwater recharge rates, flow directions, and velocities and mixing of waters from different sources. Basis for evaluating hydrologic system at YM independently of analyses based on hydraulic arguments.	

3. ☐ Model — Check all that apply

Type of Model	☐ Conceptual Model ☐ Abstraction Model ☐ Mathematical Model ☐ System Model ☐ Process Model
Intended Use of Model	☐ Input to Calculation ☐ Input to another Model or Analysis ☐ Input to Technical Document ☐ Input to Other Technical Products
Describe use:	

4. Title:

Geochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing, and Recharge at Yucca Mountain, Nevada

5. Document Identifier (including Rev. No. and Change No., if applicable):

ANL-NBS-HS-000021, Rev. 00

6. Total Attachments:

None

7. Attachment Numbers - No. of Pages in Each:

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8. Originator	Arend Meijer Ed Kwicklis	SIGNATURE ON FILE	08/17/00
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10. Lead/Supervisor	Paul Dixon	SIGNATURE ON FILE	08/17/00
11. Responsible Manager	Paul Dixon	SIGNATURE ON FILE	08/17/00

12. Remarks:

Initial Issue

OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
ANALYSIS/MODEL REVISION RECORD

Complete Only Applicable Items

2. Analysis or Model Title:

Geochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing, and Recharge at Yucca Mountain, Nevada

3. Document Identifier (including Rev. No. and Change No., if applicable):

ANL-NBS-HS-000021, Rev. 00

4. Revision/Change No.	5. Description of Revision/Change
Rev 00	Initial issue

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TABLES

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ACRONYMS

AMR	Analysis/Model Report
AR	Group of boreholes located in Amargosa River near the southwest corner of the Site Model Area
AR/FMW	Group of boreholes located near the confluence of the Amargosa River and Fortymile Wash drainages
CF	Group of boreholes located in Crater Flat
CMB	Chloride mass balance
DOE	Department of Energy
FMW-E	Group of boreholes located in the eastern part of Fortymile Wash
FMW-N	Group of boreholes located in the northern part of Fortymile Wash
FMW-S	Group of boreholes located in the southern part of Fortymile Wash
FMW-W	Group of boreholes located in the western part of Fortymile Wash
GF	Group of boreholes located near the Gravity Fault
JF	Group of boreholes located in Jackass Flats
ka	Thousand years before the present
Ma	Million years before the present
NC-EWDP	Nye County Early Warning Detection Program
NEC	Nuclear Engineering Company
NTS	Nevada Test Site
OCRWM	Office of Civilian Radioactive Waste Management
PA	Performance Assessment
pmc	Percent modern carbon
QA	Quality Assurance
QARD	Quality Assurance Requirements and Description

ACRONYMS (Continued)

SH	Group of boreholes located near Skeleton Hills and Specter Range Thrust Fault
TU	Tritium units
USGS	U. S. Geological Survey
VSMOW	Vienna Standard Mean Ocean Water
YM	Yucca Mountain
YMP	Yucca Mountain Site Characterization Project
YM-C	Group of boreholes located in the central part of Yucca Mountain
YM-E	Group of boreholes located in the eastern part of Yucca Mountain
YM-N	Group of boreholes located in the northern part of Yucca Mountain
YM-S	Group of boreholes located in the southern part of Yucca Mountain
WT	Water table

1. PURPOSE

This analysis is governed by the Office of Civilian Radioactive Waste Management (OCRWM) Analysis and Modeling Report Development Plan entitled "Geochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing and Recharge at Yucca Mountain" (CRWMS M&O 1999a). As stated in this Development Plan, the purpose of the work is to provide an analysis of groundwater recharge rates, flow directions and velocities, and mixing proportions of water from different source areas based on groundwater geochemical and isotopic data. The analysis of hydrochemical and isotopic data is intended to provide a basis for evaluating the hydrologic system at Yucca Mountain independently of analyses based purely on hydraulic arguments. Where more than one conceptual model for flow is possible, based on existing hydraulic data, hydrochemical and isotopic data may be useful in eliminating some of these conceptual models.

This report documents the use of geochemical and isotopic data to constrain rates and directions of groundwater flow near Yucca Mountain and the timing and magnitude of recharge in the Yucca Mountain vicinity. The geochemical and isotopic data are also examined with regard to the possible dilution of groundwater recharge from Yucca Mountain by mixing with groundwater downgradient from the potential repository site. Specifically, the primary tasks of this report, as listed in the AMR Development Plan (CRWMS M&O 1999a), consist of the following:

1. Compare geochemical and isotopic data for perched and pore water in the unsaturated zone with similar data from the saturated zone to determine if local recharge is present in the regional groundwater system

2. Determine the timing of the recharge from stable isotopes such as deuterium (^{2}H) and oxygen-18 (^{18}O), which are known to vary over time as a function of climate, and from radioisotopes such as carbon-14 (^{14}C) and chlorine-36 (^{36}Cl)

3. Determine the magnitude of recharge from relatively conservative tracers such as chloride and/or groundwater age and unsaturated-zone thickness

4. Correct ^{14}C ages for possible dilution of radiocarbon by calcite fracture coatings using geochemical reaction models

5. Establish mixing relations between waters from different source areas using relatively conservative species such as ^{2}H and ^{18}O or chloride and sulfate, and evaluate if inferred flow paths and mixing relations are reasonable based on chemical reactions required to reproduce the observed water chemistry.

The analysis presented in this report is appropriate for the intended use described above. This analysis is not directly related to the principal factors, or other factors, for the post-closure safety case, nor is it used directly in calculations or analyses that provide estimates of the effects of potentially disruptive processes and events, as described in AP-3.15Q, *Managing Technical Product Inputs*.

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2. QUALITY ASSURANCE

The activities documented in this Analysis and Modeling Report (AMR) were evaluated in accordance with QAP-2-0, *Conduct of Activities*, and were determined to be quality affecting and subject to the requirements of the U.S. Department of Energy (DOE) Office of Civilian Radioactive Waste Management (OCRWM) *Quality Assurance Requirements and Description* (QARD) (DOE 2000). This evaluation is documented in Activity Evaluation of M&O Site Investigations-(Q) (CRWMS M&O 1999b; 1999c) and *Activity Evaluation for Work Package WP 1301213SM1* (Wemheuer 1999). Accordingly, the analysis activities documented in this AMR have been conducted in accordance with the CRWMS M&O quality assurance (QA) program, using approved procedures identified in CRWMS M&O (1999a). This AMR has been developed in accordance with procedure AP-3.10Q, *Analyses and Models*. The conclusions in this AMR do not affect the repository design or permanent items as discussed in QAP-2-3, *Classification of Permanent Items*.

The work activities documented in the AMR depend on electronic media to store, maintain, retrieve, modify, update, and transmit quality affecting information. As part of the work process, electronic databases, spreadsheets, and sets of files were required to hold information intended for use to support the licensing position. In addition, the work process required the transfer of data and files electronically from one location to another. Consequently, all electronic files consisting of source data, developed model inputs, model outputs, and post-processing results were maintained and processed according to the seven compliance criteria listed in AP-SV.1Q, *Control of the Electronic Management of Data*, pursuant to the Work Direction and Planning Document governing these activities (CRWMS M&O 1999a).

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3. COMPUTER SOFTWARE AND MODEL USAGE

The following commercially available software (as per AP-SI.1Q, *Software Management*) was used in this analysis and documentation:

- SURFER for Windows, version 6: used to create post-plots [(Golden Software 1995); (exempt software in accordance with AP-SI.1Q)].

- TECPLOT, version 7.5: used to create *x-y* scatterplots [(AMTEC Engineering 1998); (exempt software in accordance with AP-SI.1Q)].

This software met the acceptance criteria of being able to produce plots of acceptable graphic quality in formats suitable for incorporation into this AMR.

The following public-domain geochemical software was used in this analysis:

NETPATH, version 2.13 (Plummer et al. 1994, pp. 1–30; STN: 10303-2.13-00): used to correct carbon-14 ages for the effects of chemical reactions. (Note: NETPATH is a FORTRAN program running under MS-DOS; was developed by the U.S. Geological Survey (USGS); and was run on a COMPAQ Professional Workstation AP400, with a Intel Pentium II processor, manufacturer's serial number AP400 400S1/1P/128/4S/2D+ DOM D828BZY50021, located at Los Alamos National Laboratory, TA-3, Bldg. 31.)

This software is subject to the configuration controls and qualification processes in accordance with AP-SI.1Q. The software was obtained from Configuration Management, was appropriate for its intended use, and used only within the range of validation. The range of hydrochemical data used in NETPATH for this AMR is indicated by Table 3.

The output from SURFER and TECPLOT was visually checked for correctness, and the results of all calculations using NETPATH were checked with order-of-magnitude estimations.

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4. INPUTS

4.1 DATA AND PARAMETERS

Input data directly used in this analysis come from several sources that are summarized in Table 1. Tables 2 and 3 list the chemical and isotopic groundwater data used in the analysis, including not only local data for the Yucca Mountain area but also regional data for the Death Valley flow system and Nevada Test Site (NTS). The qualification status of data inputs is indicated in the electronic Document Input Reference System (DIRS) database. Data qualification efforts, as needed, will be conducted in accordance with AP-SIII.2Q, *Qualification of Unqualified Data and the Documentation of Rationale for Accepted Data*, and documented separately from this AMR.

Table 1. Sources of Data Referenced in This Report

Input Data for Hydrogeologic Setting, Potentiometric Surface, and Previous Work (Sections 6.2, 6.3, and 6.4)

Data Description	DTN
Only corroborative data were used	N/A

Input Data for Areal Distributions of Chemical and Isotopic Species (Section 6.5.1)

Data Description	DTN
Chemical and isotopic data from borehole TW-5	MO0007GNDWTRIS.004, MO0007MAJIONPH.002
Chemical and isotopic data from the Nye County EWDP Wells in Amargosa Valley, Nevada, collected between 12/11/98 and 11/15/99.	MO0007GNDWTRIS.012, MO0007MAJIONPH.015
Chemical data from borehole NDOT collected 5/17/95	MO0007MAJIONPH.009
Chemical and isotopic data from boreholes WT-7, WT-10, WT#12, WT#14, and WT#15	MO0007GNDWTRIS.006, MO0008MAJIONPH.017
Chemical and isotopic data from the CIND-R-LITE well	GS000700012847.001
Stable isotope ratios and radiocarbon data for WT#12, WT#14, and WT#15	MO0007GNDWTRIS.007
Chemical and isotopic data from test well UE-25 p#1, Yucca Mountain area, Nye County, Nevada	MO0007GNDWTRIS.008, MO0007MAJIONPH.010
Chemical and isotopic data for groundwater in the Yucca Mountain area, Nevada 1971–1984	MO0007GNDWTRIS.009, MO0007MAJIONPH.011
Chemical analyses of water from selected wells and springs in the Yucca Mountain area, Nevada, and southeastern California	MO0007MAJIONPH.012
Chemical data from borehole USW VH-2	GS930108315213.002
Uranium isotopic analyses of groundwaters from SW Nevada – SE California	GS930108315213.004
Chemical composition of groundwater in the Yucca Mountain area	MO0007MAJIONPH.013
Chemical and isotopic data for groundwater in the west-central Amargosa Desert, Nevada	MO0007GNDWTRIS.011, MO0007MAJIONPH.014
Hydrochemical data from USW VH-1, JF#3, UE-29 UZN#91, Virgin Spring, Nevares Spring, UE-25 J-12, UE-25 J-13, UE-22 ARMY#1, and USW UZ-14	GS930908312323.003
Selected groundwater data for Yucca Mountain region, southern Nevada, through December 1992	MO0007GNDWTRIS.005, MO0007MAJIONPH.008
Hydrochemical data base for the Death Valley Region	MO0007MAJIONPH.006
Field, chemical, and isotopic data describing water samples collected in Death Valley National Monument and at various boreholes in and around Yucca Mountain, Nevada, between 1992 and 1995	GS950808312322.001

Input Data for Areal Distributions of Chemical and Isotopic Species (Section 6.5.1) Continued

Data Description	DTN
Uranium and thorium isotope data for waters analyzed between 1/94 and 9/96	GS960908315215.013
$\delta^{18}O$ and δD stable isotope analyses of borehole waters from GEXA Well 4 and VH-2	GS970708312323.001
Uranium isotopic data for SZ and UZ waters collected between 12/96 and 12/97	GS980108312322.003
Uranium isotopic data for saturated- and unsaturated-zone waters collected by non-YMP personnel between May 1989 and August 1997	GS980208312322.006
Chemical and isotopic data for groundwater samples collected at boreholes USW UZ-14, UE-25 WT#3, and UE-25 WT-17	MO0007GNDWTRIS.003, MO0007MAJIONPH.005
U concentrations and $^{234}U/^{238}U$ ratios from spring, well, runoff, and rainwaters collected from the NTS and Death Valley vicinities and analyzed between 01/15/98 and 08/15/98	GS980908312322.009
Chemical composition of groundwater from UZ#16	MO0007MAJIONPH.007
Chemical and isotopic data for borehole USW G-2	MO0007GNDWTRIS.002, MO0007MAJIONPH.003
Isotopic data for borehole USW H-6	See Assumption 23

Input Data for Regional Flow Paths Inferred from Hydrochemical Data (Section 6.5.2)

Data Description	DTN
Chemical and isotopic data from the Nye County EWDP Wells in Amargosa Valley, Nevada, collected between 12/11/98 and 11/15/99.	MO0007GNDWTRIS.012, MO0007MAJIONPH.015
Chemical data from borehole NDOT collected 5/17/95	MO0007MAJIONPH.009
Chemical and isotopic data from boreholes WT-7, WT-10, WT#12, WT#14, and WT#15	MO0007GNDWTRIS.006, MO0008MAJIONPH.017
Chemical and isotopic data from the CIND-R-LITE well	GS000700012847.001
Chemical and isotopic data from test well UE-25 p#1, Yucca Mountain area, Nye County, Nevada	MO0007GNDWTRIS.008, MO0007MAJIONPH.010
Chemical and isotopic data for groundwater in the Yucca Mountain area, Nevada 1971–1984	MO0007GNDWTRIS.009, MO0007MAJIONPH.011
Chemical analyses of water from selected wells and springs in the Yucca Mountain area, Nevada, and southeastern California	MO0007MAJIONPH.012
Chemical data from borehole USW VH-2	GS930108315213.002
Chemical composition of groundwater in the Yucca Mountain area	MO0007MAJIONPH.013
Chemical and isotopic data for groundwater in the west-central Amargosa Desert, Nevada	MO0007GNDWTRIS.011, MO0007MAJIONPH.014
Selected groundwater data for Yucca Mountain region, southern Nevada, through December 1992	MO0007GNDWTRIS.005, MO0007MAJIONPH.008
Hydrochemical data base for the Death Valley Region	MO0007MAJIONPH.006
Field, chemical, and isotopic data describing water samples collected in Death Valley National Monument and at various boreholes in and around Yucca Mountain, Nevada, between 1992 and 1995	GS950808312322.001
Chemical and isotopic data for groundwater samples collected at boreholes USW UZ-14, UE-25 WT#3, and UE-25 WT-17	MO0007GNDWTRIS.003, MO0007MAJIONPH.005
Chemical composition of groundwater from UZ#16	MO0007MAJIONPH.007
Chemical and isotopic data for borehole USW G-2	MO0007GNDWTRIS.002, MO0007MAJIONPH.003
Isotopic data for borehole USW H-6	See Assumption 23

Input Data for Evaluation of Evidence for Local Recharge (Section 6.5.3)

Data Description	DTN
Chemical and isotopic data from boreholes WT-7, WT-10, WT#12, WT#14, and WT#15	MO0007GNDWTRIS.006, MO0008MAJIONPH.017
Chemical and isotopic data for groundwater in the Yucca Mountain area, Nevada 1971–1984	MO0007GNDWTRIS.009, MO0007MAJIONPH.011
Chemical analyses of water from selected wells and springs in the Yucca Mountain area, Nevada, and southeastern California	MO0007MAJIONPH.012
Chemical data from borehole USW VH-2	GS930108315213.002
Uranium isotopic analyses of groundwaters from SW Nevada – SE California	GS930108315213.004
Chemical composition of groundwater in the Yucca Mountain area	MO0007MAJIONPH.013
Chemical and isotopic data for groundwater in the west-central Amargosa Desert, Nevada	MO0007GNDWTRIS.011, MO0007MAJIONPH.014
Hydrochemical data from USW VH-1, JF#3, UE-29 UZN#91, Virgin Spring, Nevares Spring, UE-25 J-12, UE-25 J-13, UE-22 ARMY#1, and USW UZ-14	GS930908312323.003
Hydrochemical data base for the Death Valley Region	MO0007MAJIONPH.006
Field, chemical, and isotopic data describing water samples collected in Death Valley National Monument and at various boreholes in and around Yucca Mountain, Nevada, between 1992 and 1995	GS950808312322.001
Uranium and thorium isotope data determined by mass spectrometry for dating sub-surface secondary deposits from ESF and drill hole locations	GS960208315215.001
Uranium and thorium isotope data for waters analyzed between 1/94 and 9/96.	GS960908315215.013
U and Th isotope data for ESF secondary minerals collected between 3/96 and 7/96	GS960908315215.014
Uranium and thorium isotope data collected between 9/96 and 2/97 from secondary minerals in the ESF	GS970208315215.001
Uranium-lead isotope data for ESF secondary minerals from Sep. 96 to Feb. 97	GS970208315215.002
Uranium and thorium isotope data from secondary minerals in the ESF collected between 2/15/97 and 9/15/97	GS970808315215.012
$^{234}U/^{238}U$ activity ratios for perched water	GS980108312322.003
Chemical data from borehole WT-24 collected in 1997	GS980108312322.005
Uranium isotopic data for saturated- and unsaturated-zone waters collected by non-YMP personnel between May 1989 and August 1997	GS980208312322.006
Field, chemical, and isotopic data for groundwater samples collected at boreholes USW UZ-14, UE-25 WT#3, and UE-25 WT-17	MO0007GNDWTRIS.003, MO0007MAJIONPH.005
U concentrations and $^{234}U/^{238}U$ ratios from spring, well, runoff, and rain waters collected from the NTS and Death Valley vicinities and analyzed between 01/15/98 and 08/15/98	GS980908312322.009
Chemical and isotopic data for borehole USW G-2	MO0007GNDWTRIS.002, MO0007MAJIONPH.003
Chemical composition of groundwater from UZ#16	MO0007MAJIONPH.007
$\delta^{13}C$, δD, $\delta^{18}O$, ^{14}C data for perched water samples	MO0007GNDWTRIS.013
Chemical composition of perched water samples	MO0007MAJIONPH.016
Chlorine-36 analyses of packrat urine	LAJF831222AQ98.011
Chemical and isotopic data from the Nye County EWDP Wells in Amargosa Valley, Nevada, collected between 12/11/98 and 11/15/99.	MO0007GNDWTRIS.012, MO0007MAJIONPH.015

Input Data for Evaluation of Evidence for Timing of Recharge (Section 6.5.4)

Data Description	DTN
Chemical and isotopic data from boreholes WT-7, WT-10, WT#12, WT#14, and WT#15	MO0007GNDWTRIS.006, MO0008MAJIONPH.017
Chemical and isotopic data from the CIND-R-LITE well	GS000700012847.001
Stable isotope ratios and radiocarbon data for WT#12, WT#14, and WT#15	MO0007GNDWTRIS.007
Chemical and isotopic data from test well UE-25 p#1, Yucca Mountain area, Nye County, Nevada	MO0007GNDWTRIS.008, MO0007MAJIONPH.010
Chemical and isotopic data for groundwater in the Yucca Mountain area, Nevada 1971–1984	MO0007GNDWTRIS.009, MO0007MAJIONPH.011
Chemical analyses of water from selected wells and springs in the Yucca Mountain area, Nevada, and southeastern California	MO0007MAJIONPH.012
Chemical data from borehole USW VH-2	GS930108315213.002
^{14}C activities in samples from borehole a#2	MO0007GNDWTRIS.010
Chemical and isotopic data for groundwater in the west-central Amargosa Desert, Nevada	MO0007GNDWTRIS.011, MO0007MAJIONPH.014
Hydrochemical data from USW VH-1, JF#3, UE-29 UZN#91, Virgin Spring, Nevares Spring, UE-25 J-12, UE-25 J-13, UE-22 ARMY#1, and USW UZ-14	GS930908312323.003
Selected groundwater data for Yucca Mountain region, southern Nevada, through December 1992	MO0007GNDWTRIS.005, MO0007MAJIONPH.008
Hydrochemical data base for the Death Valley Region	MO0007MAJIONPH.006
Field, chemical, and isotopic data describing water samples collected in Death Valley National Monument and at various boreholes in and around Yucca Mountain, Nevada, between 1992 and 1995	GS950808312322.001
$\delta^{18}O$ and δ D stable isotope analyses of borehole waters from GEXA Well 4 and VH-2	GS970708312323.001
Chemical and isotopic data for groundwater samples collected at boreholes USW UZ-14, UE-25 WT#3, and UE-25 WT-17	MO0007GNDWTRIS.003, MO0007MAJIONPH.005
Chemical and isotopic data for borehole USW G-2	MO0007GNDWTRIS.002, MO0007MAJIONPH.003
$\delta^{13}C$, δD, $\delta^{18}O$, and ^{14}C data for perched water	MO0007GNDWTRIS.010
Chlorine-36 analyses of packrat urine	LAJF831222AQ98.011
Isotopic data for borehole USW H-6	See Assumption 23

Input Data for Evaluation of Evidence for Mixing Relations Between Waters from Different Sources (Section 6.5.5)

Data Description	DTN
Chemical and isotopic data from the Nye County EWDP Wells in Amargosa Valley, Nevada, collected between 12/11/98 and 11/15/99.	MO0007GNDWTRIS.012, MO0007MAJIONPH.015
Chemical and isotopic data from boreholes WT-7, WT-10, WT#12, WT#14, and WT#15	MO0007GNDWTRIS.006, MO0008MAJIONPH.017
Chemical and isotopic data from the CIND-R-LITE well	GS000700012847.001
Stable isotope ratios and radiocarbon data for WT#12, WT#14, and WT#15	MO0007GNDWTRIS.007
Chemical and isotopic data from test well UE-25 p#1, Yucca Mountain area, Nye County, Nevada	MO0007GNDWTRIS.008, MO0007MAJIONPH.010
Chemical and isotopic data for groundwater in the Yucca Mountain area, Nevada 1971–1984	MO0007GNDWTRIS.009, MO0007MAJIONPH.011
Chemical composition of groundwater in the Yucca Mountain area	MO0007MAJIONPH.013
Selected groundwater data for Yucca Mountain region, southern Nevada, through December 1992	MO0007GNDWTRIS.005, MO0007MAJIONPH.008

Input Data for Evaluation of Evidence for Mixing Relations Between Waters from Different Sources (Section 6.5.5) Continued

Data Description	DTN
Field, chemical, and isotopic data describing water samples collected in Death Valley National Monument and at various boreholes in and around Yucca Mountain, Nevada, between 1992 and 1995	GS950808312322.001
$\delta^{18}O$ and δ D stable isotope analyses of borehole waters from GEXA Well 4 and VH-2	GS970708312323.001
Chemical and isotopic data for groundwater samples collected at boreholes USW UZ-14, UE-25 WT#3, and UE-25 WT-17	MO0007GNDWTRIS.003, MO0007MAJIONPH.005
Chemical and isotopic data for borehole USW G-2	MO0007GNDWTRIS.002, MO0007MAJIONPH.003
Isotopic data for borehole USW H-6	See Assumption 23

Input Data for Evaluation of Evidence for the Magnitude of Recharge (Section 6.5.6)

Data Description	DTN
Chemical and isotopic data for groundwater in the Yucca Mountain area, Nevada 1971–1984	MO0007GNDWTRIS.009, MO0007MAJIONPH.011
Chemical analyses of water from selected wells and springs in the Yucca Mountain area, Nevada, and southeastern California	MO0007MAJIONPH.012
Chemical composition of groundwater in the Yucca Mountain area	MO0007MAJIONPH.013
Chemical and isotopic data for groundwater in the west-central Amargosa Desert, Nevada	MO0007GNDWTRIS.011, MO0007MAJIONPH.014
Field, chemical, and isotopic data describing water samples collected in Death Valley National Monument and at various boreholes in and around Yucca Mountain, Nevada, between 1992 and 1995	GS950808312322.001
Chemical and isotopic data for groundwater samples collected at boreholes USW UZ-14, UE-25 WT#3, and UE-25 WT-17	MO0007GNDWTRIS.003, MO0007MAJIONPH.005
Chemical and isotopic data for borehole USW G-2	MO0007GNDWTRIS.002, MO0007MAJIONPH.003
Chemical composition of perched water samples	MO0007MAJIONPH.016
Chemical composition of groundwater from UZ#16	MO0007MAJIONPH.007
Apparent infiltration rates in alluvium from USW UZ-N37, USW UZ-N54, USW UZ-14 and UE-25 UZ#16, calculated by chloride mass balance method	LA0002JF831222.001
Apparent infiltration rates in PTn units from USW UZ-7a, USW UZ-N55, USW UZ-14, UE-25 UZ#16, USW NRG-6, USW NRG-7a, and USW SD-6, SD-7, SD-9 and SD-12, calculated by chloride mass balance method	LA0002JF831222.002

Input Data for Evaluation of Evidence for Downgradient Dilution (Section 6.5.7)

Data Description	DTN
Chemical and isotopic data from the Nye County EWDP Wells in Amargosa Valley, Nevada, collected between 12/11/98 and 11/15/99.	MO0007GNDWTRIS.012, MO0007MAJIONPH.015
Chemical and isotopic data from boreholes WT-7, WT-10, WT#12, WT#14, and WT#15	MO0007GNDWTRIS.006, MO0008MAJIONPH.017
Chemical and isotopic data from the CIND-R-LITE well	GS000700012847.001
Stable isotope ratios and radiocarbon data for WT#12, WT#14, and WT#15	MO0007GNDWTRIS.007
Chemical and isotopic data from test well UE-25 p#1, Yucca Mountain area, Nye County, Nevada	MO0007GNDWTRIS.008, MO0007MAJIONPH.010
Chemical and isotopic data for groundwater in the Yucca Mountain area, Nevada 1971–1984	MO0007GNDWTRIS.009, MO0007MAJIONPH.011

Input Data for Evaluation of Evidence for Downgradient Dilution (Section 6.5.7) Continued

Data Description	DTN
Uranium isotopic analyses of groundwaters from SW Nevada – SE California	GS930108315213.004
Chemical composition of groundwater in the Yucca Mountain area	MO0007MAJIONPH.013
Chemical and isotopic data for groundwater in the west-central Amargosa Desert, Nevada	MO0007GNDWTRIS.011, MO0007MAJIONPH.014
Hydrochemical data from USW VH-1, JF#3, UE-29 UZN#91, Virgin Spring, Nevares Spring, UE-25 J-12, UE-25 J-13, UE-22 ARMY#1, and USW UZ-14	GS930908312323.003
Selected groundwater data for Yucca Mountain region, southern Nevada, through December 1992	MO0007GNDWTRIS.005, MO0007MAJIONPH.008
Field, chemical, and isotopic data describing water samples collected in Death Valley National Monument and at various boreholes in and around Yucca Mountain, Nevada, between 1992 and 1995	GS950808312322.001
Uranium and thorium isotope data for waters analyzed between 1/94 and 9/96	GS960908315215.013
$\delta^{18}O$ and δD stable isotope analyses of borehole waters from GEXA Well 4 and VH-2	GS970708312323.001
Uranium isotopic data for SZ and UZ waters collected between 12/96 and 12/97	GS980108312322.003
Chemical and isotopic data for groundwater samples collected at boreholes USW UZ-14, UE-25 WT#3, and UE-25 WT-17	MO0007GNDWTRIS.003, MO0007MAJIONPH.005
U concentrations and $^{234}U/^{238}U$ ratios from spring, well, runoff, and rain waters collected from the NTS and Death Valley vicinities and analyzed between 01/15/98 and 08/15/98	GS980908312322.009
Chemical and isotopic data for borehole USW G-2	MO0007GNDWTRIS.002, MO0007MAJIONPH.003
Isotopic data for borehole USW H-6	See Assumption 23

The input data listed in Table 1 represent geochemical and isotopic characteristics of perched water and groundwater in the vicinity of Yucca Mountain and hence are appropriate for the intended use of this AMR.

4.2 CRITERIA

This AMR complies with the Department of Energy (DOE) interim guidance (Dyer 1999). Subparts of the interim guidance that apply to this analysis are those pertaining to the characterization of the Yucca Mountain site (Subpart B, Section 15), the compilation of information regarding geochemistry and mineral stability of the site in support of the License application (Subpart B, Section 21(c)(1)(ii)), and the definition of geochemical parameters and conceptual models used in performance assessment (Subpart E, section 114(a)).

4.3 CODES AND STANDARDS

No specific formally established codes or standards have been identified as applying to this analysis and modeling activity. This activity does not directly support License Application (LA) design.

Table 2. Summary of Groundwater Wells and Data Sources Used in This Report

Well identifier	Abbreviation used in report	Fig. 2 sample	UTM-X (m)	UTM-Y (m)	Area[a]		Approximate interval sampled (m)	Geologic unit[b]	Reference for sampled depth and chemical (C) and isotopic (I) data[c]
UE-29 a#2	a#2(dp)	1	555753	4088351	FM-N	Fortymile Wash–North	247–354	Th	DTN: MO0007GNDWTRIS.010 (I), MO0007MAJIONPH.013 (C)
	a#2(sh)	2					87–213	Th	
UE-25 J-12	J-12	3	554444	4068774	FM-N	Fortymile Wash–North	open borehole (226–347)	Tv	DTN: MO0007GNDWTRIS.010 (I), MO0007MAJIONPH.013 (C)
UE-25 J-13	J-13	4	554017	4073517	FM-N	Fortymile Wash–North	open borehole (282–1063)	Tpt	
UE-25 JF#3	JF#3	5	554498	4067974	FM-N	Fortymile Wash–North	open borehole (216–347)	Tv	DTN: MO0007GNDWTRIS.005(I), MO0007MAJIONPH.008 (C), GS930908312323.003 (I)
UE-25 WT#14	WT#14	6	552630	4077330	FM-N	Fortymile Wash–North	open borehole (346–399)	Th	DTN: MO0007GNDWTRIS.007 (I), MO0007GNDWTRIS.006 (I), MO0008MAJIONPH.017 (C)
UE-25 WT#15	WT#15	7	554034	4078702	FM-N	Fortymile Wash–North	Open borehole (354–415)	Tpt	
USW G-2	G-2	8	548143	4082542	YM-N	Yucca Mountain–North	Open borehole (534–1831)	Th/Tct	DTN: MO0007GNDWTRIS.002 (I), MO0007MAJIONPH.003 (C)
USW UZ-14	UZ-14(sh)	9	548032	4080260	YM-N	Yucca Mountain–North	bailed (579)	Tcp	DTN: MO0007GNDWTRIS.003 (I), MO0007MAJIONPH.005 (C)
	UZ-14(dp)	10					bailed (655)	Tcb	
USW H-1	H-1(Tcp)	11	548727	4079926	YM-N	Yucca Mountain–North	572–687	Tcp	DTN: MO0007GNDWTRIS.010 (I), MO0007MAJIONPH.013 (C)
	H-1(Tcb)	12					687–1829	Tcb	
UE-25 b#1	b#1(bh)	13	549949	4078423	YM-N	Yucca Mountain–North	open borehole (470–1220)	Th/Tct	DTN: MO0007GNDWTRIS.010 (I), MO0007MAJIONPH.013 (C)
	b#1(Tcb)	14					863–875	Tcb	
UE-25 c#1	c#1	15	550955	4075933	YM-E	Yucca Mountain–East	open borehole (400–914)	Tcb/Tct	DTN: MO0007GNDWTRIS.009 (I), MO0007MAJIONPH.011 (C), MO0007MAJIONPH.012 (C)
UE-25 c#2	c#2	16	550955	4075871	YM-E	Yucca Mountain–East	open borehole (401–913)	Tcb	
UE-25 c#3	c#3	17	550930	4075902	YM-E	Yucca Mountain–East	open borehole (402–913)	Tcb/Tct	
	c#3('95)	18					open borehole (402–913)	Tcb/Tct	DTN: GS950808312322.001 (C,I)
UE-25 ONC#1	ONC#1	19	550479.9	4076608	YM-E	Yucca Mountain–East	open borehole (433–469)	Th/Tcp	MO0007MAJIONPH.004 (C)
UE-25 p#1	P#1(v)	20	551501	4075659	YM-E	Yucca Mountain–East	381–1197	Tcp	DTN: MO0007GNDWTRIS.009 (I), MO0007MAJIONPH.011 (C), MO0007GNDWTRIS.008 (I), MO0007MAJIONPH.010 (C)
	P#1(c)	21					1297–1805	DSlm	
USW G-4	G-4	22	548933	4078602	YM-C	Yucca Mountain–Central	open borehole (541–915)	Tct	DTN: MO0007GNDWTRIS.010 (I), MO0007MAJIONPH.013 (C)
USW H-3	H-3	23	547562	4075759	YM-C	Yucca Mountain–Central	open borehole (822–1220)	Tct	DTN: MO0007GNDWTRIS.009 (I), MO0007MAJIONPH.011 (C), MO0007MAJIONPH.012 (C)
USW H-4	H-4	24	549188	4077309	YM-C	Yucca Mountain–Central	open borehole (519–1220)	Tcb/Tct	DTN: MO0007GNDWTRIS.010 (I), MO0007MAJIONPH.013 (C)
USW H-5	H-5	25	547668	4078841	YM-C	Yucca Mountain–Central	open borehole (704–1220)	Tcb/Tct	
UE-25 UZ#16	UZ#16	26	549484.9	4076986	YM-C	Yucca Mountain–Central	490–492	Tcp	DTN: MO0007MAJIONPH.007 (C)

Table 2 (Continued). Sources of Groundwater Samples Used in This Report

Well identifier	Abbreviation used in report	Fig. 2 sample	UTM-X (m)	UTM-Y (m)	Area[a]		Approximate interval sampled (m)	Geologic unit[b]	Reference for sampled depth and chemical (C) and isotopic (I) data[c]
UE-25 WT#12	WT#12	27	550168	4070659	YM-S	Yucca Mountain–South	open borehole (345–399)	Tpt/Th	DTN: MO0007GNDWTRIS.007 (I), MO0007GNDWTRIS.006 (I), MO0008MAJIONPH.017 (C)
USW WT-17	WT-17	28	549905	4073307	YM-S	Yucca Mountain–South	open borehole (depth not reported)	Tcp	DTN: MO0007GNDWTRIS.003 (I), MO0007MAJIONPH.005 (C)
UE-25 WT#3	WT#3	29	552090	4072550	YM-S	Yucca Mountain–South	open borehole (depth not reported)	Tcb	DTN: MO0007GNDWTRIS.003 (I), MO0007MAJIONPH.005 (C)
USW H-6	H-6(bh)	30	546188	4077816	CF	Crater Flat	open borehole (526–1220)	Tcb/Tct	DTN: MO0007GNDWTRIS.010 (I), MO0007MAJIONPH.013 (C)
	H-6(Tct)	31					753–835	Tct	DTN: MO0007MAJIONPH.012 (C), See Assumption 23 (C,I)
	H-6(Tcb)	32					608–646	Tcb	
USW WT-7	WT-7	33	546151	4075474	CF	Crater Flat	open borehole (421–491)	Tv	DTN: MO0007GNDWTRIS.006 (I), MO0008MAJIONPH.017 (C)
USW WT-10	WT-10	34	545964	4073378	CF	Crater Flat	open borehole (347–431)	Tpt	
USW VH-1	VH-1	35	539976	4071714	CF	Crater Flat	open borehole (184–762)	Tcb	DTN: MO0007GNDWTRIS.010 (I), MO0007MAJIONPH.013 (C)
USW VH-2	VH-2	36	537738	4073214	CF	Crater Flat	open borehole (164–1219)	Tv	DTN: GS930108315213.002 (C), GS970708312323.001 (I) MO0007MAJIONPH.008 (C)
Gexa Well 4	Gexa Well 4	37	534069	4086110	CF	Crater Flat	open borehole (188–488)	Tv	DTN: GS970708312323.001 (I), MO0007MAJIONPH.008 (C)
NC-EWDP-2D	NC-EWDP-2D	38	547744	4057164	NC-EWDP	Nye County EWDP	not reported	not reported	DTN: MO0007GNDWTRIS.012 (I), MO0007MAJIONPH.015 (C)
NC-EWDP-5S	NC-EWDP-5S	39	555676	4058229	NC-EWDP	Nye County EWDP	not reported	not reported	
NC-EWDP-3D	NC-EWDP-3D	40	541273	4059444	NC-EWDP	Nye County EWDP	not reported	not reported	
NC-EWDP-9S	NC-EWDP-9S	41	539039	4061004	NC-EWDP	Nye County EWDP	not reported	not reported	
NC-EWDP-1D	NC-EWDP-1D	42	536768	4062502	NC-EWDP	Nye County EWDP	not reported	not reported	
CIND-R-LITE	CIND-R-LITE	43	544027	4059809	NC-EWDP	Nye County EWDP	not reported	Tv	DTN: GS930108315213.002 (C), MO0007MAJIONPH.006 (C), GS000700012847.001 (C,I)
UE-25 J-11	J-11	44	563799	4071058	JF	Jackass Flats	open borehole (317–405)	Tb	DTN: MO0007MAJIONPH.012 (C)
15S/50E-19b1	15S/50E-19b1	45	553862.5	4054720	LW	Amargosa Valley (formerly Lathrop Wells)	open borehole (103–110)	Qal	DTN: MO0007MAJIONPH.006 (C)
Airport Well	Airport Well	46	552818	4054929	LW	Amargosa Valley	open borehole (76–229)	Qal	DTN: MO0007MAJIONPH.008 (C)
15S/50E-18cdc	15S/50E-18cdc	47	553934.3	4055151	LW	Amargosa Valley	open borehole (105–120)	Qal	DTN: MO0007MAJIONPH.006 (C) Claassen 1985, Table 1, sample 34

Table 2 (Continued). Sources of Groundwater Samples Used in This Report

Well identifier	Abbreviation used in report	Fig. 2 sample	UTM-X (m)	UTM-Y (m)	Area[a]		Approximate interval sampled (m)	Geologic unit[b]	Reference for sampled depth and chemical (C) and isotopic (I) data[c]
NDOT	NDOT	48	553685	4055242	LW	Amargosa Valley	open borehole (105–151)	Qal	DTN: MO0007MAJIONPH.008 (C), MO0007MAJIONPH.009 (C)
15S/50E-18ccc	15S/50E-18ccc	49	553710	4055273	LW	Amargosa Valley	open borehole (105–120)	Qal	DTN: MO0007MAJIONPH.006 (C), Claassen 1985, Table 1, sample 35
16S/48E-23da	16S/48E-23da	51	542391	4044364	FMW-S	Fortymile Wash–South	open borehole (24–140)	Qal	DTN: MO0007MAJIONPH.006 (C) Claassen 1985, Table 1, sample 53
15S/49E-22a1	15S/49E-22a1	52	550086.3	4054974	FMW-S	Fortymile Wash–South	open borehole (90–174)	Qal	DTN: MO0007MAJIONPH.006 (C)
16S/49E-05acc	16S/49E-05acc	53	546664.5	4049439	FMW-S	Fortymile Wash–South	open borehole (21–90)	Qal	DTN: MO0007MAJIONPH.012 (C), MO0007GNDWTRIS.011 (I), MO0007MAJIONPH.014 (C), Claassen 1985, Table 1, sample 4
15S/49E-27acc	15S/49E-27acc	54	549552.9	4052722	FMW-S	Fortymile Wash–South	open borehole (73–467)	Qal	DTN: MO0007MAJIONPH.012 (C)
15S/49E-22dcc	15S/49E-22dcc	55	549672.5	4053523	FMW-S	Fortymile Wash–South	open borehole (78–148)	Qtal	DTN: MO0007MAJIONPH.006 (C), MO0007GNDWTRIS.011 (I, “Amargosa Well 3”)
15S/49E-22dc	15S/49E-22dc	56	549697	4053524	FMW-S	Fortymile Wash–South	open borehole (78–150)	Qal	DTN: MO0007MAJIONPH.012 (C), MO0007GNDWTRIS.011 (I), MO0007MAJIONPH.014 (C), Claassen 1985, Table 1, sample 3
16S/49E-8abb	16S/49E-8abb	57	546695	4048453	FMW-S	Fortymile Wash–South	open borehole (45–60)	Qal	DTN: MO0007MAJIONPH.012 (C), MO0007GNDWTRIS.011 (I), MO0007MAJIONPH.014 (C), Claassen 1985, Table 1, sample 5
16S/49E-8acc	16S/49E-8acc	58	546723	4047806	FMW-S	Fortymile Wash–South	open borehole (45–90)	Qal	DTN: MO0007MAJIONPH.012 (C), Claassen 1985, Table 1, sample 6
16S/49E-9cda	16S/49E-9cda	59	548168	4047291	FMW-S	Fortymile Wash–South	open borehole (46–90)	Qal	DTN: MO0007MAJIONPH.012 (C), Claassen 1985, Table 1, sample 7
16S/49E-9dcc	16S/49E-9dcc	60	548343	4047045	FMW-S	Fortymile Wash–South	open borehole (49–60)	Qal	DTN: MO0007MAJIONPH.012 (C), MO0007GNDWTRIS.011 (I), MO0007MAJIONPH.014 (C), Claassen 1985, Table 1, sample 8
16S/49E-18dc	16S/49E-18dc	61	545144	4045579	FMW-S	Fortymile Wash–South	open borehole (33–110)	Qal	DTN: MO0007MAJIONPH.012 (C), MO0007GNDWTRIS.011 (I), MO0007MAJIONPH.014 (C), Claassen 1985, Table 1, sample 9
16S/49E-16ccc	16S/49E-16ccc	62	547508	4045222	FMW-S	Fortymile Wash–South	open borehole (depth not reported)	Qal	DTN: MO0007MAJIONPH.012 (C), MO0007GNDWTRIS.011 (I), MO0007MAJIONPH.014 (C), Claassen 1985, Table 1, sample 10

Table 2 (Continued). Sources of Groundwater Samples Used in This Report

Well identifier	Abbreviation used in report	Fig. 2 sample	UTM-X (m)	UTM-Y (m)	Area[a]		Approximate interval sampled (m)	Geologic unit[b]	Reference for sampled depth and chemical (C) and isotopic (I) data[c]
16S/49E-19daa	16S/49E-19daa	63	545777	4044535	FMW-S	Fortymile Wash–South	open borehole (30–90)	Qal	DTN: MO0007MAJIONPH.012 (C), MO0007GNDWTRIS.011 (I), MO0007MAJIONPH.014 (C), Claassen 1985, Table 1, sample 11
16S/48E-24aaa	16S/48E-24aaa	64	544077	4045235	FMW-S	Fortymile Wash–South	open borehole (29–150)	Qal	DTN: MO0007MAJIONPH.012 (C), Claassen 1985, Table 1, sample 12
16S/48E-25aa	16S/48E-25aa	65	544160	4043602	FMW-S	Fortymile Wash–South	open borehole (26–50)	Qal	DTN: MO0007MAJIONPH.012 (C), MO0007GNDWTRIS.011 (I), MO0007MAJIONPH.014 (C), Claassen 1985, Table 1, sample 13
16S/48E-36aaa	16S/48E-36aaa	66	544168	4042031	FMW-S	Fortymile Wash–South	open borehole (21–50)	Qal	DTN: MO0007MAJIONPH.012 (C), MO0007GNDWTRIS.011 (I), MO0007MAJIONPH.014 (C), Claassen 1985, Table 1, sample 14
17S/48E-1ab	17S/48E-1ab	67	544152	4040182	FMW-S	Fortymile Wash–South	open borehole (16–60)	Qal	DTN: MO0007MAJIONPH.012 (C), MO0007GNDWTRIS.011 (I), MO0007MAJIONPH.014 (C), Claassen 1985, Table 1, sample 15
17S/49E-7bb	17S/49E-7bb	68	544758	4038645	FMW-S	Fortymile Wash–South	open borehole (12–150)	Qal	DTN: MO0007MAJIONPH.012 (C), MO0007GNDWTRIS.011 (I), MO0007MAJIONPH.014 (C), Claassen 1985, Table 1, sample 16
17S/49E-8ddb	17S/49E-8ddb	69	547575	4037612	FMW-S	Fortymile Wash–South	Open borehole (15–100)	Qal	DTN: MO0007MAJIONPH.012 (C), MO0007GNDWTRIS.011 (I), MO0007MAJIONPH.014 (C), Claassen 1985, Table 1, sample 18
16S/49E-23add	16S/49E-23add	70	551958	4045217	FMW-S	Fortymile Wash–South	open borehole (depth not reported)	Qal	DTN: MO0007MAJIONPH.012 (C), MO0007GNDWTRIS.011 (I), MO0007MAJIONPH.014 (C), Claassen 1985, Table 1, sample 21
16S/48E-23bdb	16S/48E-23bdb	71	541469	4044729	FMW-S	Fortymile Wash–South	open borehole (29–50)	Qal	DTN: MO0007MAJIONPH.012 (C), Claassen 1985, Table 1, sample 24
16S/48E-36dcc	16S/48E-36dcc	72	543530	4040395	FMW-S	Fortymile Wash–South	open borehole (13–120)	Qal	DTN: MO0007MAJIONPH.012 (C), Claassen 1985, Table 1, sample 26
17S/49E-9aa	17S/49E-9aa	73	549262	4038515	FMW-E	Fortymile Wash–East	open borehole (depth not reported)	Qal	DTN: MO0007MAJIONPH.012 (C), MO0007GNDWTRIS.011 (I), MO0007MAJIONPH.014 (C), Claassen 1985, Table 1, sample 17

Table 2 (Continued). Sources of Groundwater Samples Used in This Report

Well identifier	Abbreviation used in report	Fig. 2 sample	UTM-X (m)	UTM-Y (m)	Area[a]		Approximate interval sampled (m)	Geologic unit[b]	Reference for sampled depth and chemical (C) and isotopic (I) data[c]
17S/49E-15bbd	17S/49E-15bbd	74	549843	4036855	FMW-E	Fortymile Wash–East	open borehole (17–110)	Qal	DTN: MO0007MAJIONPH.012 (C), MO0007GNDWTRIS.011 (I), MO0007MAJIONPH.014 (C), Claassen 1985, Table 1, sample 19
17S/49E-35ddd	17S/49E-35ddd	75	552739	4031202	FMW-E	Fortymile Wash–East	discharge, Ash Tree Spring	Qal	DTN: MO0007MAJIONPH.012 (C), MO0007GNDWTRIS.011 (I), MO0007MAJIONPH.014 (C), Claassen 1985, Table 1, sample 20
17S/49E-15bc	17S/49E-15bc	76	549870	4036577	FMW-E	Fortymile Wash–East	open borehole (depth not reported)	Qal	DTN: MO0007MAJIONPH.012 (C), Claassen 1985, Table 1, sample 38
16S/48E-15dda	16S/48E-15dda	77	540893	4045620	FMW-W	Fortymile Wash–West	open borehole (depth not reported)	Qal	DTN: MO0007MAJIONPH.012 (C), Claassen 1985, Table 1, sample 22
16S/48E-15aaa	16S/48E-15aaa	78	540838	4046636	FMW-W	Fortymile Wash–West	open borehole (29–50)	Qal	DTN: MO0007MAJIONPH.012 (C), MO0007GNDWTRIS.011 (I), MO0007MAJIONPH.014 (C), Claassen 1985, Table 1, sample 23
16S/48E-10cba	16S/48E-10cba	79	539766	4047463	FMW-W	Fortymile Wash–West	open borehole (depth not reported)	Qal	DTN: MO0007MAJIONPH.012 (C), MO0007GNDWTRIS.011 (I), MO0007MAJIONPH.014 (C), Claassen 1985, Table 1, sample 25
16S/48E-15ba	16S/48E-15ba	80	539670	4046693	FMW-W	Fortymile Wash–West	open borehole (30–50)	Qal	DTN: MO0007MAJIONPH.012 (C), Claassen 1985, Table 1, sample 37
TW-5	TW-5	81	562604	4054686	SH	Skeleton Hills	open borehole (207–244)	Qal	DTN: MO0007MAJIONPH.006 (C) MO0007GNDWTRIS.004 (I), MO0007MAJIONPH.002 (C),
16S/50E-7bcd	16S/50E-7bcd	82	553757	4047786	SH	Skeleton Hills	open borehole (43–60)	Qal	DTN: MO0007MAJIONPH.012 (C), MO0007GNDWTRIS.011 (I), MO0007MAJIONPH.014 (C), Claassen 1985, Table 1, sample 27
16S/49E-12ddd	16S/49E-12ddd	83	553834	4047386	SH	Skeleton Hills	open borehole (depth not reported)	Qal	DTN: MO0007MAJIONPH.012 (C). Claassen 1985, Table 1, sample 28
16S/49E-15aaa	16S/49E-15aaa	84	550556	4046842	SH	Skeleton Hills	open borehole (51–120)	Qal	DTN: MO0007MAJIONPH.012 (C), MO0007GNDWTRIS.011 (I), MO0007MAJIONPH.014 (C), Claassen 1985, Table 1, sample 29
16S/49E-36aaa	16S/49E-36aaa	85	553569	4042053	GF	Gravity Fault	open borehole (depth not reported)	Qal	DTN: MO0007GNDWTRIS.011 (I), MO0007MAJIONPH.014 (C), Claassen 1985, Table 1, sample 30
16S/49E-36aba	16S/49E-36aba	86	553222	4041836	GF	Gravity Fault	open borehole (depth not reported)	Qal	DTN: MO0007MAJIONPH.012 (C), Claassen 1985, Table 1, sample 31

Table 2 (Continued). Sources of Groundwater Samples Used in This Report

Well identifier	Abbreviation used in report	Fig. 2 sample	UTM-X (m)	UTM-Y (m)	Area[a]		Approximate interval sampled (m)	Geologic unit[b]	Reference for sampled depth and chemical (C) and isotopic (I) data[c]
16S/49E-35aaa	16S/49E-35aaa	87	551980	4041520	GF	Gravity Fault	open borehole (depth not reported)	Qal	DTN: MO0007MAJIONPH.012 (C), Claassen 1985, Table 1, sample 32
16S/49E-35baa	16S/49E-35baa	88	551307	4042040	GF	Gravity Fault	open borehole (depth not reported)	Qal	DTN: MO0007MAJIONPH.012 (C), Claassen 1985, Table 1, sample 33
17S/49E-11ba	17S/49E-11ba	89	551873	4038623	GF	Gravity Fault	open borehole (depth not reported)	Qal	DTN: MO0007MAJIONPH.012 (C), Claassen 1985, Table 1, sample 36
18S/50E-6dac	18S/50E-6dac	90	556035	4029960	GF	Gravity Fault	open borehole (depth not reported)	Qal	DTN: MO0007MAJIONPH.012 (C), Claassen 1985, Table 1, sample 43
17S/50E-19aab	17S/50E-19aab	91	555998	4035691	GF	Gravity Fault	open borehole (depth not reported)	Qal	DTN: MO0007MAJIONPH.012 (C), Claassen 1985, Table 1, sample 58
18S/50E-7aa	18S/50E-7aa	92	556040	4029158	GF	Gravity Fault	open borehole (depth not reported)	Qal	DTN: MO0007MAJIONPH.014 (C), Claassen 1985, Table 1, sample 59
17S/49E-28bcd	17S/49E-28bcd	93	548370	4033395	AR/FMW	Amargosa River / Fortymile Wash	open borehole (depth not reported)	Qal	DTN: MO0007MAJIONPH.012 (C)
18S/49E-1aba	18S/49E-1aba	94	554035	4031056	AR/FMW	Amargosa River / Fortymile Wash	0	Qal	DTN: MO0007MAJIONPH.014 (C), Claassen 1985, Table 1, sample 40
18S/49E-2cbc	18S/49E-2cbc	95	551377	4030023	AR/FMW	Amargosa River / Fortymile Wash	open borehole (22–160)	Qal	DTN: MO0007MAJIONPH.012 (C), Claassen 1985, Table 1, sample 41
18S/49E-11bbb	18S/49E-11bbb	96	551307	4029283	AR/FMW	Amargosa River / Fortymile Wash	open borehole (depth not reported)	Qal	DTN: MO0007MAJIONPH.012 (C), Claassen 1985, Table 1, sample 42
17S/49E-29acc	17S/49E-29acc	97	547349	4033420	AR/FMW	Amargosa River / Fortymile Wash	open borehole (depth not reported)	Qal	DTN: MO0007MAJIONPH.012 (C), Claassen 1985, Table 1, sample 44
16S/48E-8ba	16S/48E-8ba	98	536979	4048129	AR	Amargosa River	open borehole (34–80)	Qal	DTN: MO0007MAJIONPH.012 (C), Claassen 1985, Table 1, sample 45
16S/48E-7bba	16S/48E-7bba	99	534791	4048366	AR	Amargosa River	open borehole (depth not reported)	Qal	DTN: MO0007MAJIONPH.012 (C), Claassen 1985, Table 1, sample 46
16S/48E-7cbc	16S/48E-7cbc	100	534546	4047441	AR	Amargosa River	open borehole (depth not reported)	Qal	DTN: MO0007MAJIONPH.012 (C), MO0007GNDWTRIS.011 (I), MO0007MAJIONPH.014 (C), Claassen 1985, Table 1, sample 47
16S/48E-18bcc	16S/48E-18bcc	101	534827	4045747	AR	Amargosa River	open borehole (depth not reported)	Qal	DTN: MO0007MAJIONPH.012 (C), Claassen 1985, Table 1, sample 48
16S/48E-17ccc	16S/48E-17ccc	102	536122	4045106	AR	Amargosa River	open borehole (depth not reported)	Qal	DTN: MO0007MAJIONPH.012 (C), Claassen 1985, Table 1, sample 49
16S/48E-18dad	16S/48E-18dad	103	536069	4045814	AR	Amargosa River	open borehole (depth not reported)	Qal	DTN: MO0007MAJIONPH.012 (C), MO0007GNDWTRIS.011 (I), MO0007MAJIONPH.014 (C), Claassen 1985, Table 1, sample 50

Table 2 (Continued). Sources of Groundwater Samples Used in This Report

Well identifier	Abbreviation used in report	Fig. 2 sample	UTM-X (m)	UTM-Y (m)	Area[a]		Approximate interval sampled (m)	Geologic unit[b]	Reference for sampled depth and chemical (C) and isotopic (I) data[c]
16S/48E-8cda	16S/48E-8cda	104	537063	4045941	AR	Amargosa River	open borehole (depth not reported)	Qal	DTN: MO0007MAJIONPH.012 (C), Claassen 1985, Table 1, sample 51
16S/48E-17abb	16S/48E-17abb	105	537035	4046681	AR	Amargosa River	open borehole (31–90)	Qal	DTN: MO0007MAJIONPH.012 (C), Claassen 1985, Table 1, sample 52
27N/4E-27bbb	27N/4E-27bbb	106	541520	4034130	AR	Amargosa River	open borehole (14–90)	Qal	DTN: MO0007MAJIONPH.012 (C), Claassen 1985, Table 1, sample 54
Nucl. Eng. Co.	NEC Well	107	527519	4068738	AR	Amargosa River	open borehole (86–180)	Qal	DTN: MO0007GNDWTRIS.011 (I), MO0007MAJIONPH.014 (C), Claassen 1985, Table 1, sample 60

DTN: As listed in the reference column of this table

NOTES: [a]See Figure 2 and Section 6.5.1 for a definition of subareas in the vicinity of Yucca Mountain.

[b]Geologic units: Qal Quaternary alluvium; Qtal Quaternary-Tertiary alluvium; Tv Tertiary volcanic rocks; Tb Tertiary basalts; Tpt Tertiary Topopah Spring Member of Paintbrush Tuff; Tct Tertiary Crater Flat Tuff; Th Tertiary tuffaceous beds of Calico Hills; Tac Calico Hills Formation; Tcb Tertiary Bullfrog Member of Crater Flat Tuff; Tcp Tertiary Prow Pass Member of Crater Flat Tuff; DSlm Devonian and Silurian Lone Mountain Dolomite (Oliver and Root 1997, p. 5; Buesch et al. 1996, Table 4; Day et al. 1998, map sheet 2). Also, see stratigraphy column in Figure 3.

[c]C: the DTN or reference was the source for chemical data for this well; I: the DTN or reference was the source for isotopic data for this well. References to sample identifiers in Claassen (1985, Table 1) provide traceability between identifiers used in the listed DTNs and those listed in column 1 of this table.

Table 3. Chemical and Isotopic Compositions of Groundwater Samples Used in This Report (data sources listed in Table 2)

Fig. 2 Well Name[a]	Fig. 2 sample No.	Area	pH	Chemical concentrations (mg L^{-1})								Isotopic analyses				Calculated values[b]		
				Ca	Mg	Na	K	Cl	SO_4	HCO_3	SiO_2	$\delta^{13}C$ (per mil)	^{14}C activity (pmc)	δD (per mil)	$\delta^{18}O$ (per mil)	log P_{CO2} (atm)	IAP/K_{cal}	(Ca+Mg)/ (Na+K) (meq meq^{-1})
a#2(dp)	1	FM-N	7.2	10	0.2	44	1.1	11	22	107	44	–12.6	62.3	–93.5	–12.8	–2.164	0.07	0.265
a#2(sh)	2	FM-N	7.0	10	0.3	44	1.3	8.8	21	107	44	–13.1	60.0	–93.0	–12.8	–1.978	0.041	0.269
J-12	3	FM-N	7.1	14	2.1	38	5.1	7.3	22	119	54	–7.9	32.2	–97.5	–12.8	–2.008	0.09	0.489
J-13	4	FM-N	7.2	12	2.1	42	5	7.1	17	124	57	–7.3	29.2	–97.5	–13.0	–2.063	0.116	0.395
JF#3	5	FM-N	7.7	18	3.1	38	8.9	10	30	120	56	–8.6	30.7	–97	–13.2	–2.613	0.439	0.613
WT#14	6	FM-N	7.3	10	0.8	45	5	8.2	22	119	57	–12.75	24.1	–97.5	–12.75	–2.154	0.107	0.271
WT#15	7	FM-N	7.5	12	1.7	62	4.6	12	16	166	52	–11.8	21.6	–97.5	–13.2	–2.26	0.27	0.262
G-2	8	YM-N	7.5	7.7	0.47	46	5.3	6.5	15	121	51	–11.8	20.5	–98.8	–13.33	–2.352	0.161	0.198
UZ-14(sh)[c]	9	YM-N	8.4	0.48	0.023	70.0	1.9	6.7	14	133	44	–14.1	24.6	–100.4	–14.0	—	—	0.008
UZ-14(dp)[c]	10	YM-N	8.4	0.21	0.030	74	1.9	7.7	14	137	47	–14.4	21.1	–100.6	–14.0	—	—	0.004
H-1(Tcp)	11	YM-N	7.7	4.5	<0.1	51	2.4	5.7	18	115	47	—	19.9	–103	–13.4	–2.583	0.136	0.102
H-1(Tcb)	12	YM-N	7.5	6.2	<0.1	51	1.6	5.8	19	122	40	–11.4	23.9	–101	–13.5	–2.345	0.132	0.141
b#1(bh)[c]	13	YM-N	7.3	18	0.66	49.5	3.6	10.75	23	156	52.5	–10.55	16.7	–100.3	–13.4	–2.036	0.318	0.424
b#1(Tcb)	14	YM-N	7.1	18	0.72	46	2.8	7.5	21	133	51	–8.6	18.9	–99.5	–13.5	–1.892	0.175	0.462
c#1	15	YM-E	7.6	11	0.34	56	2.0	7.4	23	151	56	–7.1	15	–102	–13.5	–2.309	0.426	0.232
c#2	16	YM-E	7.7	12	0.4	54	2.1	7.1	22	139	54	–7	16.6	–100	–13.4	–2.454	0.524	0.263
c#3	17	YM-E	7.7	11	0.4	55	1.9	7.2	22	137	53	–7.5	15.7	–103	–13.5	–2.458	0.479	0.238
c#3('95)	18	YM-E	7.7	11	0.3	57	1.9	6.5	19	141	58	—	—	–99.7	–13.38	–2.4	0.471	0.227
ONC#1	19	YM-E	8.7	13	1.1	51	3.6	7.1	24	115[d]	27	—	—	—	—	—	—	0.32
p#1(v)	20	YM-E	6.8	37	10	92	5.6	13	38	344	49	–4.2	3.5	–106	–13.5	–1.229	0.397	0.644
P#1(c)	21	YM-E	6.6	100	39	150	12	28	160	694	41	–2.3	2.3	–106	–13.8	–0.661	1.404	1.2
G-4	22	YM-C	7.7	13	0.2	57	2.1	5.9	19	139	45	–9.1	22	–103	–13.8	–2.488	0.494	0.263
H-3	23	YM-C	9.2	0.8	0.02	120	1.1	9.5	31	274	43	–4.9	10.5	–101	–13.9	–3.854	0.808	0.008
H-4	24	YM-C	7.4	17	0.29	73	2.6	6.9	26	173	46	–7.4	11.8	–104	–14.0	–2.099	0.377	0.269
H-5[c]	25	YM-C	7.85	1.95	0.01	60	2.1	6.1	16	126.5	48	–10.3	19.8	–102	–13.6	–2.729	0.109	0.037
UZ#16	26	YM-C	—	11.4	1.6	79.2	—	10.6	29.1	210	36.2	—	—	—	—	—	—	0.547
WT#12	27	YM-S	7.6	15	0.3	66	2.6	7.8	28	167	47	–8.1	11.4	–102.5	–13.75	–2.303	0.469	0.263
WT-17[c]	28	YM-S	7.1	8.9	0.85	49.0	2.6	6.4	17.5	129.5	39.0	–8.3	16.2	–101.9	–13.7	—	—	0.234
WT#3[c]	29	YM-S	7.6	11.2	1.0	49.0	3.9	6.0	18.3	138.5	56.2	–8.2	22.3	–102.1	–13.6	—	—	0.287

Table 3 (Continued). Chemical and Isotopic Compositions of Groundwater Samples Used in This Report (data sources listed in Table 2)

Fig. 2 Well Name[a]	Fig. 2 sample No.	Area	pH	Chemical concentrations (mg L^{-1})								Isotopic analyses				Calculated values[b]		
				Ca	Mg	Na	K	Cl	SO_4	HCO_3	SiO_2	$\delta^{13}C$ (per mil)	^{14}C activity (pmc)	δD (per mil)	$\delta^{18}O$ (per mil)	log P_{CO2} (atm)	IAP/K_{cal}	(Ca+Mg)/ (Na+K) (meq meq^{-1})
H-6(bh)	30	CF	8.1	4.1	0.09	86	1.3	7.6	29	182	48	–7.5	16.3	–106	–13.8	–2.764	0.501	0.056
H-6(Tct)	31	CF	8.3	1.4	0.02	88	1.3	7.2	25	217	47	–7.3	10.0	–105	–14.0	–2.868	0.342	0.019
H-6(Tcb)	32	CF	8.3	4.7	0.07	88	1.4	7.4	32	234	49	–7.1	12.4	–107	–14.0	–2.868	1.071	0.062
WT-7	33	CF	8.7	2.6	0.18	97	2.1	13	7.2	252	20	–9.01	—	—	–13.95	–3.272	1.36	0.034
WT-10[c]	34	CF	8.4	2.6	0.045	94.5	1	7.8	33.5	186	46.5	–6.1	7.3	–103	–13.82	–3.055	0.603	0.032
VH-1[c]	35	CF	7.6	10.3	1.53	79	1.9	10.33	44.33	164.7	49.7	–8.5	12.2	–108	–14.2	–2.355	0.411	0.184
VH-2[c]	36	CF	7.1	78.5	29.75	70.8	8.1	16	142.5	391.8	26.25	—	—	–99.4	–13.4	—	—	1.937
Gexa Well 4[c]	37	CF	7.9	11.5	0.37	71	3.25	13.5	45.5	150	48	—	—	–105.55	–14.1	—	—	0.191
NC-EWDP-2D[c]	38	NC-EWDP	7.5	19	1.2	42	4.1	6.1	22	149	49	–8.3	23.5	–104	–14.1	—	—	0.57
NC-EWDP-5S[c]	39	NC-EWDP	8.3	17	3.5	149	11	39	146	—	—	—	—	–107	–14	—	—	0.177
NC-EWDP-3D[c]	40	NC-EWDP	8.4	0.51	0.07	113	3.0	9.0	45	223	54	–6.8	10	–105.6	–14.4	—	—	—
NC-EWDP-9S[c]	41	NC-EWDP	8.0	20.3	7.7	76	4.3	11.0	61.7	212	52	–6.5	—	–104.2	–14.0	—	—	—
NC-EWDP-1D[c]	42	NC-EWDP	7.2	55.5	31	73.5	10	16	136	369	46.5	–4.5	—	–101.3	–13.5	—	—	—
CIND-R-LITE[c]	43	NC-EWDP	7.8	12.33	6.17	71.7	3.97	9.23	46	193.7	54.3	—	—	–102	–13.65	—	—	0.349
J-11	44	JF	7.6	82	13	143	15	18	449	102	68	—	—	—	—	—	—	0.782
15S/50E-19b1	45	LW	8.1	20	3.9	107.5	6	17.5	127.5	167.5	43	—	—	—	—	—	—	0.273
Airport Well	46	LW	9	5.6	0.23	70	1.5	10	46	110	40	—	—	—	—	—	—	0.097
15S/50E-18cdc	47	LW	8	12	0.5	93	3.9	13.1	100	157	34	—	—	—	—	—	—	0.159
NDOT[c]	48	LW	8	16.33	0.813	101.3	3.83	14.67	110	160	43.7	—	—	—	—	—	—	0.196
15S/50E-18ccc	49	LW	8.4	16.8	0.5	93.1	3.9	13.1	100	157	34.3	—	—	—	—	—	—	0.212
16S/48E-23da	51	FMW-S	8.2	22	2.2	69	6.6	26.6	67.2	134.2	—	—	—	—	—	—	—	0.4
15S/49E-22a1	52	FMW-S	8	25	2.4	41	5.2	8	33	145	52	—	—	—	—	—	—	0.754
16S/49E-05acc	53	FMW-S	8.1	29	2.2	35	5.1	6	26	135	62	–7.1	19.3	–103	–13.2	—	—	0.982
15S/49E-27acc	54	FMW-S	7.8	22	1.6	48	2.9	7.3	36	151	19	—	—	—	—	—	—	0.569
15S/49E-22dcc	55	FMW-S	6.7	27	2.0	43	4.6	8.5	33	149	49	–10.2	15.6	–102	–12.8	—	—	0.760
15S/49E-22dc[c]	56	FMW-S	7.8	26.9	1.9	43	4.7	8.5	32.7	148.9	49.3	—	15.6	–102	–12.8	—	—	0.75
16S/49E-8abb	57	FMW-S	7.5	30.1	2.7	37	5.5	7.8	29.8	151.9	54.1	–6.8	21.4	–99.5	–13.2	—	—	0.98
16S/49E-8acc	58	FMW-S	7.9	22.8	2.4	37	6.6	6.0	28.8	137.9	58.3	—	—	—	—	—	—	0.75
16S/49E-9cda	59	FMW-S	7.6	30.5	3.4	51	8.6	12.1	64.4	143.4	65.5	—	—	—	—	—	—	0.74

Table 3 (Continued). Chemical and Isotopic Compositions of Groundwater Samples Used in This Report (data sources listed in Table 2)

Fig. 2 Well Name[a]	Fig. 2 sample No.	Area	pH	Chemical concentrations (mg L^{-1})								Isotopic analyses				Calculated values[b]		
				Ca	Mg	Na	K	Cl	SO_4	HCO_3	SiO_2	$\delta^{13}C$ (per mil)	^{14}C activity (pmc)	δD (per mil)	$\delta^{18}O$ (per mil)	log P_{CO2} (atm)	IAP/K_{cal}	(Ca+Mg)/ (Na+K) (meq meq^{-1})
16S/49E-9dcc	60	FMW-S	8.2	22.8	2.7	56.1	9.0	9.9	67.2	140.9	72.1	–7.3	21.9	–103	–13.4	—	—	0.51
16S/49E-18dc	61	FMW-S	8.1	20.0	2.7	42.1	9.0	7.4	27.9	150.1	58.9	—	28.4	–102	–12.6	—	—	0.59
16S/49E-16ccc	62	FMW-S	7.9	30.1	1.9	39.8	4.3	8.2	50.9	132.4	76.9	–5.2	24.8	–97.5	–13.2	—	—	0.9
16S/49E-19daa	63	FMW-S	8.2	24.0	1.2	36.1	8.2	6.7	32.7	134.2	75.1	—	20.8	–101	–13.1	—	—	0.73
16S/48E-24aaa	64	FMW-S	8.1	18.0	0.7	54	7.0	7.8	29.8	147.1	78.7	—	—	—	—	—	—	0.38
16S/48E-25aa	65	FMW-S	8.1	18.8	0.7	43	7.4	9.2	27.9	133.0	72.1	—	19.3	–102	–13.0	—	—	0.49
16S/48E-36aaa	66	FMW-S	8.4	16.8	1.9	40	6.3	6.7	25.0	133.0	78.7	—	—	–98.5	–12.6	—	—	0.53
17S/48E-1ab	67	FMW-S	8.2	18.8	1.5	40	7	6.4	25.0	134.8	78.7	—	18.4	–104	–13.0	—	—	0.55
17S/49E-7bb	68	FMW-S	8.3	24.0	1.7	48	7.4	9.6	30.7	153.2	79.9	—	10.0	–104	–12.7	—	—	0.59
17S/49E-8ddb	69	FMW-S	8.4	20.8	2.7	36.1	7.4	6.4	26.9	123.3	80.8	—	27.8	–102	–13.0	—	—	0.72
16S/49E-23add	70	FMW-S	8.2	16	1.7	55.9	6.5	8.9	34.6	126.9	76.3	–8.4	27.4	–99	–13.2	—	—	0.36
16S/48E-23bdb	71	FMW-S	7.3	9.2	1.0	66.0	6.6	8.9	26.9	156.2	73.9	—	—	—	—	—	—	0.18
16S/48E-36dcc	72	FMW-S	7.2	54.9	9.7	100.0	12.9	33.0	110.5	300.2	70.3	—	—	—	—	—	—	0.76
17S/49E-9aa	73	FMW-E	8.0	24.8	3.6	48.0	9.8	9.9	69.2	131.2	70.3	—	18.9	–105	–12.8	—	—	0.66
17S/49E-15bbd	74	FMW-E	8.1	20.8	3.9	31.3	8.2	9.9	34.6	120.2	72.7	—	40.3	—	—	—	—	0.87
17S/49E-35ddd	75	FMW-E	8.0	15.2	4.6	50.6	8.2	6.7	40.3	157.4	81.1	—	13.8	–102	–12.4	—	—	0.47
17S/49E-15bc	76	FMW-E	8.2	21.6	1.0	39.1	6.6	10.6	27.9	122.0	—	—	—	—	—	—	—	0.62
16S/48E-15dda	77	FMW-W	8.0	20.0	5.8	70.8	7.4	17.4	37.5	175.7	71.5	—	—	—	—	—	—	0.45
16S/48E-15aaa	78	FMW-W	8.1	9.6	3.2	57.9	5.9	7.4	27.9	153.2	67.9	–7.1	17.1	–103	–13.4	—	—	0.28
16S/48E-10cba	79	FMW-W	8.3	9.2	3.9	60.9	5.5	8.2	32.7	166	64.3	–5.6	15.6	–102	–13.4	—	—	0.28
6S/48E-15ba	80	FMW-W	8	60.1	7.8	147.1	9.8	65.6	198.8	264.2	37.3	—	—	—	—	—	—	0.55
TW-5	81	SH	7.9	33	17	130	12	21	99	395	19	—	—	–113.2	–15.4	—	—	0.51
16S/50E-7bcd	82	SH	7.6	47.7	17.5	111.5	12.9	29.1	151.8	291.7	28.8	–3.6	7.0	–105	–13.8	—	—	0.74
16S/49E-12ddd	83	SH	7.6	45.7	17	120.0	4.3	24.1	160.4	288.6	20.4	—	—	—	—	—	—	0.69
16S/49E-15aaa	84	SH	7.7	40.9	7.5	80.0	9.8	23	129.7	195.3	46.3	–3.4	—	–105	–13.8	—	—	0.71
16S/49E-36aaa	85	GF	7.8	52.1	22.1	120.0	18.0	26.9	168.1	314.2	37.9	–4.4	10.3	–104	–13.7	—	—	0.78
16S/49E-36aba	86	GF	7.7	44.9	19.9	110.1	16.8	24.1	155.6	292.9	42.7	—	—	—	—	—	—	0.74
16S/49E-35aaa	87	GF	7.7	44.1	16.0	120.0	16.0	29.1	147.9	271.5	36.7	—	—	—	—	—	—	0.63
16S/49E-35baa	88	GF	7.4	53.3	18.0	113.1	13.3	31.2	170	302.7	37.9	—	—	—	—	—	—	0.79
17S/49E-11ba	89	GF	8.1	40.1	14.1	97.0	14.1	28.0	160.4	209.9	52.9	—	—	—	—	—	—	0.69

Table 3 (Continued). Chemical and Isotopic Compositions of Groundwater Samples Used in This Report (data sources listed in Table 2)

Fig. 2 Well Name[a]	Fig. 2 sample No.	Area	pH	Chemical concentrations (mg L^{-1})								Isotopic analyses				Calculated values[b]		
				Ca	Mg	Na	K	Cl	SO_4	HCO_3	SiO_2	$\delta^{13}C$ (per mil)	^{14}C activity (pmc)	δD (per mil)	$\delta^{18}O$ (per mil)	log P_{CO2} (atm)	IAP/K_{cal}	(Ca+Mg)/ (Na+K) (meq meq^{-1})
18S/50E-6dac	90	GF	8.2	23.6	11.9	102.5	13.7	20.6	106.6	230.0	80.5	—	—	—	—	—	—	0.45
17S/50E-19aab	91	GF	8.6	7.6	8.5	252.0	27.4	69.8	175.8	415.5	42.7	—	—	—	—	—	—	0.09
18S/50E-7aa	92	GF	8.4	25.7	9.5	140.9	19.2	37.6	147	261.2	47.5	—	—	—	—	—	—	0.31
17S/49E-28bcd	93	AR/FMW	7.6	42.9	10.0	100.0	12.1	24.1	89.3	294.7	70.3	—	—	—	—	—	—	0.64
18S/49E-1aba	94	AR/FMW	8.6	24.0	11.9	94.9	19.2	18.1	99.9	263.0	72.7	—	—	—	—	—	—	0.47
18S/49E-2cbc	95	AR/FMW	7.8	28.9	11.9	120.0	9.8	19.9	74.0	352.1	58.9	—	—	—	—	—	—	0.44
18S/49E-11bbb	96	AR/FMW	7.6	34.1	8.5	99.1	11.7	30.8	90.3	224.6	78.1	—	—	—	—	—	—	0.52
17S/49E-29acc	97	AR/FMW	7.6	54.1	15.1	160.0	19.9	69.8	186.4	275.8	72.1	—	—	—	—	—	—	0.53
16S/48E-8ba	98	AR	7.9	58.5	6.3	180.5	12.9	79.8	202.7	295.9	37.9	—	—	—	—	—	—	0.42
16S/48E-7bba	99	AR	7.4	52.9	9.5	140.0	10.2	63.1	179.6	250.8	69.1	—	—	—	—	—	—	0.54
16S/48E-7cbc	100	AR	7.7	46.9	16	130.1	9.4	62.0	179.6	239.2	64.3	–6.2	31.4	–102	–13.1	—	—	0.62
16S/48E-18bcc	101	AR	8.0	54.9	10.9	150.1	11.7	61.0	190.2	271.5	79.9	—	—	—	—	—	—	0.53
16S/48E-17ccc	102	AR	7.7	66.1	10.9	169.9	12.1	83.0	235.3	239.2	77.5	—	—	—	—	—	—	0.55
16S/48E-18dad	103	AR	7.7	52.9	8.5	149.9	10.6	63.1	187.3	236.1	76.9	–5.7	—	–104	–13.6	—	—	0.49
16S/48E-8cda	104	AR	7.6	48.1	6.8	160.0	10.2	67.0	179.6	264.2	67.9	—	—	—	—	—	—	0.41
16S/48E-17abb	105	AR	7.4	60.1	7.8	157.0	12.1	69.1	178.7	302.0	75.1	—	—	—	—	—	—	0.51
27N/4E-27bbb	106	AR	7.8	58.1	19.0	134.0	19.2	31.9	106.6	438.1	72.1	—	—	—	—	—	—	0.71
NEC Well	107	AR	7.6	54.9	14.1	170.1	10.2	79.1	190.2	328.3	70.3	–5.9	28.8	—	—	—	—	0.51

DTN: See Table 2

NOTES: [a]dp = deep sample, sh = shallow sample, Tcp = sample from Prow Pass Tuff, Tcb = sample from Bullfrog Tuff, bh = sample from entire borehole, '95 = sample from 1995, v = sample from volcanic aquifer, c = sample from carbonate aquifer, Tct = sample from Tram Member or Crater Flat Tuff. Where not otherwise indicated, sample is from entire open interval of borehole.

[b] These values are for reference only. The logarithm of carbon dioxide partial pressure (log P_{CO_2}) and the ratio of the calcium-bicarbonate ion activity product to the calcite equilibrium constant (IAP/K_{cal}) were determined using NETPATH (Plummer et al. 1994, pp. 1–30). Values presented for log P_{CO_2} and IAP/K_{cal} were calculated only for groundwater samples for which ^{14}C-age corrections were made.

[c]Average value

[d]This sample also contained 8.8 mg L^{-1} carbonate (DTN: MO0007MAJIONPH.004)

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5. ASSUMPTIONS

The analyses presented in this report sometimes required that assumptions be made concerning certain aspects of the hydrochemical or hydrologic system. Typically, these assumptions were made (1) to simplify a problem so that a solution could be approximated, (2) to obtain bounding estimates, or (3) because no relevant data were available at the time the analysis was made. In this section, these assumptions are listed along with the basis for the assumption, an indication as to whether or not the assumption is to be verified, where it is used in the report, and where the conclusions are likely to have been affected by the assumption (Table 4).

Table 4. Assumptions Used in This Report

	Assumption	Rationale for assumption	TBV	Section
1	Reported chemical and isotopic data for pore water, perched water, and saturated-zone groundwater are of sufficient quantity and quality that meaningful inferences can be made about the hydrologic system in the vicinity of Yucca Mountain.	Standard quality-control measures used by the laboratories producing the chemical data include analyses of blanks, standards, and replicates. In addition, the data are used in this report to define general qualitative trends, such that outliers, if present, can be distinguished from the general population. It is acknowledged that spatial gaps in the data impart uncertainties.	No	Throughout Secs. 6, 7, basis for conclusions in Sec. 7.7
2	Water samples are representative of the hydrogeologic units from which they were collected. Mineral precipitation or equilibration with atmospheric gases at atmospheric pressure and temperature have not altered the sample water compositions during sampling.	In general, water samples were collected from boreholes from which many borehole volumes of groundwater had been pumped prior to sampling. Only in a few cases, primarily where groundwater samples were bailed from boreholes drilled for unsaturated-zone testing (UZ-holes) or water-table monitoring (WT-holes), were the boreholes not properly developed prior to sampling. For many of the other boreholes, lithium bromide was used as a tracer during drilling; samples were not collected until lithium concentrations decreased to low levels, indicating that most of the drilling fluid had been removed. Where calcite saturation indices and P_{CO2} partial pressures were calculated, the groundwater samples are unsaturated with respect to calcite and have log P_{CO2} partial pressures greater than atmospheric log P_{CO2} partial pressure (–3.5), indicating calcite precipitation or equilibration with the atmosphere gases did not occur.	No	Throughout Secs. 6, 7
3	It is assumed that the hydraulic conductivity and transmissivity of the volcanic rocks are isotropic and, thus, that flow lines can be drawn perpendicular to the hydraulic gradient.	In spite of the likely anisotropy introduced by the presence of north and northwest trending faults in the Yucca Mountain area, this assumption was made to get an overall sense of the flow directions indicated by the hydraulic gradients. The likelihood that actual flow directions may be more aligned with fault orientations than indicated by these flow lines is acknowledged in the text.	No	Sec. 6.3, Fig. 4, affects conclusions in Sec. 7.1 and 7.7

Table 4. Assumptions Used in This Report (Continued)

	Assumption	Rationale for assumption	TBV	Section
4	Regional flow paths can be traced by linking areas with similar chemical and isotopic compositions in a downgradient direction.	This is a purely simplifying assumption and clearly identified as such in the text. The 2-D nature of the analysis implicitly assumes the constancy of chemical compositions with depth in the water-table aquifer and ignores the possible chemical changes that may result from local recharge or vertical mixing between aquifers.	No	Sec. 6.5.2, Fig. 17, affects conclusions in Sec. 7.1
5	It is assumed for the purpose of tracing flow lines from chemical and isotopic data that, once in the saturated-zone groundwater system, δD, $\delta^{18}O$, Cl^-, SO_4^{2-}, Na^+, and Ca^{2+} are sufficiently conservative to identify likely flow paths.	This assumption is acknowledged in the text as an approximation. Changes in the input concentrations of these constituents as a result of climate change, or modifications to some of these constituents because of water/rock interaction, is expected to result in variability along a flow path in some or all of these constituents. However, in many cases, the areal contrast in concentrations between at least some of these constituents is large enough that meaningful inferences about flow directions can be made.	No	Secs. 6.5.2, 6.5.5, Fig. 17, affects conclusions in Secs. 7.1, 7.4
6	The $^{234}U/^{238}U$ ratio of Yucca Mountain recharge is elevated relative to the ratio in other recharge areas, so that elevated $^{234}U/^{238}U$ ratios in groundwater downgradient of Yucca Mountain can be used to identify the presence of Yucca Mountain recharge	Some variability in the $^{234}U/^{238}U$ ratio of Yucca Mountain recharge is indicated by the differences in the $^{234}U/^{238}U$ ratios of perched water at boreholes UZ-14, WT-24, and SD-7 (Table 7). The lower $^{234}U/^{238}U$ ratios of perched water at borehole SD-7 in southern Yucca Mountain approaches the $^{234}U/^{238}U$ ratios of groundwater in the surrounding areas. The perched-water data from UZ-14 and WT-24 indicate that even under relatively high recharge conditions presumed to have existed during the late Pleistocene, some recharge had elevated $^{234}U/^{238}U$ ratios, an argument supported by elevated $^{234}U/^{238}U$ ratios in groundwater at some downgradient boreholes.	No	Secs. 6.5.3.1, 6.5.7.1, affects conclusions in Secs. 7.2, 7.6
7	The offset of the δD and $\delta^{18}O$ values of the most isotopically depleted groundwater near Yucca Mountain from the present-day Yucca Mountain meteoric water line (Fig. 21) indicates paleoclimatic effects, rather than evaporation or water/rock interaction.	The dependence of the deuterium excess (the constant in the equation for the meteoric water line when the slope is 8) on the relative humidity over the moisture source area is established by theory (Clark and Fritz 1997, p. 45). Also, this assumption is supported by a correlation between δD and ^{14}C (Figure 27), and between $\delta^{18}O$ and ^{14}C, which shows that groundwater becomes more depleted with respect to δD and $\delta^{18}O$ with increasing ^{14}C age.	No	Sec. 6.5.4.1, Fig. 21, affects conclusions in Sec. 7.3
8	It can be assumed that groundwater flow to Yucca Mountain from areas directly north of Yucca Mountain is minor, particularly in areas south of Drillhole Wash.	This assumption is based on the southeastward direction of the hydraulic gradient north of Drillhole Wash, and the likelihood that northwest-southeast trending faults present in this area impart anisotropy that enhances flow along the trend of the faults. (See section 7.7.1).	TBV	Secs. 6.5.3, 6.5.5.1, 6.5.7, affects conclusions in 7.2, 7.4, 7.6, 7.7.1

Table 4. Assumptions Used in This Report (Continued)

	Assumption	Rationale for assumption	TBV	Section
9	Cl^- is relatively conservative in the groundwater system and the effects of water/rock interactions on this constituent are negligibly small.	In the saturated zone, minerals containing Cl^- are rare in the Yucca Mountain area.	No	Secs. 6.5.2, 6.5.5.1, 6.5.5.2, Table 10, Fig. 24, affects conclusions in Secs. 7.1, 7.4, 7.5, Fig. 17
10	For the purposes of modeling the interaction between meteoric water and mineral phases using NETPATH, the dissolved concentrations of Fe and Al are assumed to be negligibly small, such that these elements remain in the solid phases.	Fe and Al are only sparingly soluble under oxidizing conditions and neutral pH, which is typical of groundwaters under consideration.	No	Sec. 6.5.4.2
11	The chemical and isotopic composition of the groundwater sample from the carbonate aquifer at borehole p#1 (sample p#1(c) in table 3) and, in particular, its Cl^- concentration, are representative of the composition of groundwater in carbonate aquifer at Yucca Mountain.	Borehole p#1 is the only borehole near Yucca Mountain where groundwater was directly sampled from the carbonate aquifer, so this assumption is made out of necessity. The Cl^- concentration of groundwater at p#1 (0.79 mmol L^{-1}) is at the high end of the range of Cl^- concentrations for the carbonate aquifer measured at Ash Meadows (0.59 to 0.76 mmol L^{-1}), which may indicate the extent of the variability that could be expected at Yucca Mountain.	No	Sec. 6.5.5.2, Fig. 24, affects conclusions in Sec. 7.4
12	The estimated range of annual deposition rates for chloride at Yucca Mountain encompasses the present-day rate as well as the rates that prevailed when the sampled pore waters infiltrated below the soil zone.	This assumption is supported by several independent lines of evidence. First, the range of deposition rates assumed for Yucca Mountain encompass the present-day rates calculated for sites at Red Rock Canyon and Kawich Range, Nevada, which represent climates that are drier and wetter, respectively, than that prevailing at Yucca Mountain today. The second line of evidence is the constancy of the $^{36}Cl/Cl$ ratio throughout the Holocene, based on packrat midden data (Plummer et al., 1997). Finally, the nearly uniform Cl concentrations in the perched water and SZ groundwaters beneath Yucca Mountain also support the assumption. However, what is still needed is an estimate of the uncertainty in this deposition rate, and propagation of that uncertainty through the resulting estimates of recharge obtained by the chloride mass-balance method (see Assumption 13).	TBV	Secs. 6.5.3.2, 6.5.5.1, 6.5.6, Table 10, affects conclusions in Secs. 7.2, 7.5, 7.7.2

Table 4. Assumptions Used in This Report (Continued)

	Assumption	Rationale for assumption	TBV	Section
13	The CMB method is assumed to be applicable to the estimation of recharge rates at Yucca Mountain. The CMB method assumes one-dimensional, downward piston flow in the soil zone, no run-on or runoff, no Cl^- source other than precipitation, and no Cl^- sink (e.g., the formation of halite is negligible).	The absence of chloride sources and sinks is indicated by the absence of halite or other Cl-bearing minerals in the soils and rocks at Yucca Mountain. The departures of actual flow conditions from the assumption of one-dimensional piston flow are mitigated somewhat for calculations done on the basis of the saturated-zone chloride data. This is because, for Yucca Mountain as a whole, flow can be assumed to be vertical between the ground surface and the water table, even though lateral flow in the unsaturated zone could redistribute water on a more local scale. Similarly, when using the saturated-zone data with the CMB method, the effects of non-piston flow are mitigated because hydrodynamic mixing and mixing in the wellbore when groundwater is pumped tend to average the chloride concentrations of fast- and slow-moving water percolating through fractures and matrix in the unsaturated zone. Run-on and run-off both can redistribute chloride locally at Yucca Mountain. However, although run-on is a factor to consider for wells near Fortymile Wash, run-on from other areas to Yucca Mountain does not occur and so the total chloride balance for Yucca Mountain itself is not affected by this process. Run-off from Yucca Mountain to Fortymile Wash would tend to cause the actual chloride deposition rates at Yucca Mountain to be less than those assumed in the calculation (105 mg Cl^- cm^{-2} yr^{-1}) and thus cause the estimated Yucca Mountain recharge rates to overestimate the actual recharge.	TBV	Secs. 6.5.3.2, 6.5.6.1, Table 10, affects conclusions in Secs. 7.2, 7.5
14	The ^{14}C activities of the carbon-bearing phases assumed to be available to react with meteoric water in the NETPATH model (Plummer et al. 1994, pp. 1–30) are 100 pmc for CO_2 gas and 0 pmc for calcite and dolomite.	The ^{14}C activities of CO_2 gas in the atmosphere and shallow soil zone have probably been near 100 pmc prior to the onset of atmospheric nuclear weapons testing. However, the ^{14}C activity of CO_2 gas in the deep UZ is less than 25 pmc, so the NETPATH model implicitly assumes that the water dissolved CO_2 in the shallow soil zone. If recharge water acquired some of its CO_2 in the deep UZ, its actual age would be less than the NETPATH-corrected age. Conversely, the NETPATH model assumes that all calcite and dolomite are completely depleted in ^{14}C, a reasonable assumption based on measurements made on fracture-deposited calcite deep in the UZ. However, if meteoric water interacted with calcite in the shallow soil zone, where the ^{14}C activities of calcite may be substantially nonzero, the actual age of the groundwater would be greater than the NETPATH-corrected ages.	No	Sec. 6.5.4.2, Table 8, affects conclusions in Secs. 7.3, 7.5

Table 4. Assumptions Used in This Report (Continued)

15	The mineral phases assumed to interact with meteoric water in the NETPATH models (Section 6.5.4.2) are present in the Yucca Mountain environment, either as primary or secondary minerals in the rock, or as windblown dust deposited at the ground surface.	All minerals assumed in the NETPATH age-correction models are confirmed to be present in the Yucca Mountain environment with the exception of dolomite, which is assumed to be available as dust deposited at the ground surface. This is a plausible but unconfirmed scenario based on the presence of dolomite outcrops at Bare Mountain, in the direction of the prevailing winds. In any case, the presence of dolomite is invoked to provide a source for Mg^{2+}. Because most groundwaters to which the model was applied are low in Mg^{2+}, very little dolomite is predicted to dissolve in the meteoric water and the corrected ages are little affected by this assumption.	No	Sec. 6.5.4.2, Table 8, affects conclusions in Secs. 7.3, 7.5
16	The composition of meteoric water can be approximated as pure water in equilibrium with an atmospheric CO_2 concentration of $10^{-3.5}$ atm with no other ions present in the meteoric water.	This assumption implicitly ignores the concentration increases that all ions in the meteoric water undergo during evapotranspiration. The effect of this assumption is that, because evaporative increases in dissolved ion concentrations are ignored, the NETPATH age-correction models (Section 6.5.4.2) overestimate the amount of calcite and dolomite that have been dissolved and, hence, tend to underestimate the ages that would be calculated if such evaporative increases in concentrations had been considered. The effects of this assumption are clearly identified in the discussion of the models in Section 6.5.4.2.	No	Sec. 6.5.4.2, Table 8, affects conclusions in Secs. 7.3, 7.5
17	Carbon isotope exchange is not a significant process affecting ^{14}C activities of groundwater near Yucca Mountain.	The NETPATH age-correction models (Section 6.5.4.2) did not consider the process of carbon-isotope exchange, a process that alters the carbon isotope composition of groundwater without increasing the net concentrations of elements contained in the carbon-bearing solid phases. Isotope exchange is important to consider where the groundwater is already saturated with calcite and additional interaction between groundwater and calcite that might alter the isotopic composition (^{14}C and $\delta^{13}C$) of the dissolved carbon would not be reflected by a change in the concentration of the total dissolved carbon. The groundwater in the carbonate aquifer is already saturated with calcite and, thus, exchange reactions are important to consider in this environment. In the volcanic aquifer, almost all groundwater samples for which calcite saturation indices have been calculated are undersaturated with calcite. Any interaction between groundwater and calcite in the volcanic aquifer should, therefore, be reflected by an increase in the dissolved carbon concentrations in the groundwater, a process already considered by the mass-balance approach embedded in the NETPATH modeling.	No	Sec. 6.5.4.2, Table 8, affects conclusions in Secs. 7.3, 7.5

Table 4. Assumptions Used in This Report (Continued)

	Assumption	Rationale for assumption	TBV	Section
18	The chemical composition of groundwater at borehole J-11 is representative of groundwater in central Jackass Flats.	Because borehole J-11 is the only borehole that has been drilled and sampled in central Jackass Flats, this is a necessary assumption.	No	Sec. 6.5.7.2
19	The δD and $\delta^{18}O$ compositions of groundwater are not substantially modified by water/rock interaction with carbonate alluvium.	This assumption was used to infer that groundwater in the vicinity of the Skeleton Hills is groundwater from the carbonate aquifer in the eastern Amargosa Desert, based on their similar δD and $\delta^{18}O$ compositions, rather than chemically modified recharge from Fortymile Wash. It is generally accepted that the $\delta^{18}O$ composition of groundwater is unaffected by water/rock interaction at groundwater temperatures typical of the area and that δD values would be unaffected because of the trace levels of hydrogen in the rock (Clark and Fritz 1997, pp. 247–249).	No	Sec. 6.5.7.2.1
20	Groundwater near Fortymile Wash in the Amargosa Desert is assumed to have been recharged by water having an initial ^{14}C activity similar to that at borehole a#2 (65 pmc).	The assumption is reasonable, although difficult to prove, given the similarity of the environments and the likely cause of recharge (periodic channel runoff). The assumption leads to calculated ages between 7,000 and 15,500 years for groundwater in the Amargosa Desert near Fortymile Wash. Estimated ages based on other initial ^{14}C activities are also provided in Section 6.5.4.2.	No	Sec. 6.5.4.2
21	The variability in U concentrations and $^{234}U/^{238}U$ ratios of saturated-zone groundwater are attributable to differences in the U concentrations and $^{234}U/^{238}U$ ratios of recharge water. Once in the saturated zone, the U concentrations and $^{234}U/^{238}U$ ratios of water are unaltered by water/rock interaction and are potentially affected only by groundwater mixing.	The U concentrations of groundwater in the immediate Yucca Mountain area do not vary substantially (less than a factor of 2), indicating that relatively little U is being added as a result of water/rock interaction in the saturated zone. Under oxidizing conditions, U seems to have very low affinity for sorption onto the rock as indicated by its low K_d values (DTN: LAIT831341AQ96.001, SEP Table S97026.004).	No	Sec. 6.5.3.1, 6.5.7.1
22	Water coming from north or NW of Yucca Mountain does not have high $^{234}U/^{238}U$ activity ratios characteristic of some Yucca Mountain perched waters.	Data from groundwater immediately north and NW of Yucca Mountain are sparse, so this assumption is difficult to validate. However, on the basis of hydraulic gradients and fault orientations in northern Yucca Mountain, groundwater flow directly from the north under Yucca Mountain may be small (see Assumption 8)	TBV	Sec. 6.5.7.1, affects conclusions in Sec. 7.1
23	Chemical and isotopic data reported for borehole USW H-6 in USGS (n.d.) are representative of the sampled intervals and hence are appropriate to use to establish geochemical constraints on groundwater flow paths in the vicinity of Yucca Mountain.	The data in USGS (n.d.) are all that are available regarding the chemical and isotopic compositions of groundwater from the deeper portion of USW H-6. However, these data are consistent with data from the same stratigraphic intervals in other boreholes in the Yucca Mountain vicinity.	No	Sec. 6.5.1, 6.5.2, 6.5.4, 6.5.5, 6.5.7

DTN: N/A

Note: TBV: To be verified

6. ANALYSIS/MODEL

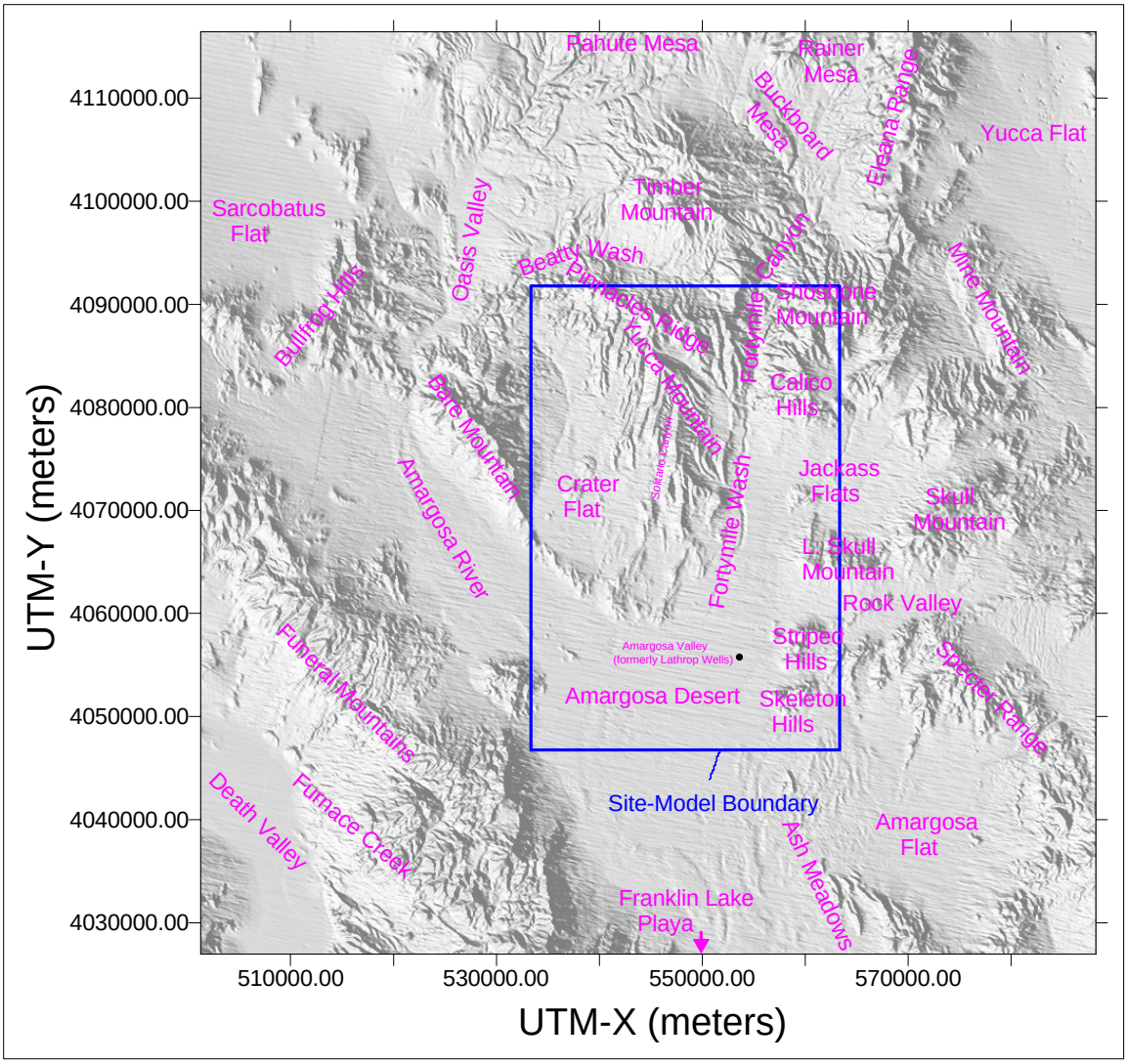
6.1 GEOGRAPHIC AND GEOLOGIC SETTING

Yucca Mountain is located in the Great Basin about 150 km northwest of Las Vegas, Nevada. The mountain consists of a series of fault-bounded blocks of ash-flow and ash-fall tuffs and a smaller volume of lava deposited between 14 and 11 Ma (million years before present) from a series of calderas located a few to several tens of kilometers to the north (Sawyer et al. 1994, Fig. 1). Yucca Mountain itself extends southward from the Pinnacles Ridge toward the Amargosa Desert, where the tuffs thin and pinch out beneath the alluvium (Figure 1). The tuffs dip 5 to 10 degrees to the east over most of Yucca Mountain. Crater Flat is west of Yucca Mountain and separated from it by Solitario Canyon, which is the surface expression of the Solitario Canyon Fault—a steeply dipping scissors fault with down-to-the-west displacement of as much as 500 m in southern Yucca Mountain (Day et al. 1998, pp. 6–7). Underlying Crater Flat is a thick sequence of alluvium, lavas, and tuffs that has been locally cut by faults and volcanic dikes. East of Yucca Mountain, and separated from it by Fortymile Wash, is Jackass Flats, which is underlain by a thick sequence of alluvium and volcanic rocks. Timber Mountain, approximately 25 km to the north of the potential repository area, is a resurgent dome within the larger caldera complex that erupted the tuffs at Yucca Mountain.

The central block of Yucca Mountain, into which waste would be emplaced if the site were licensed, is bounded by Drill Hole Wash on the north, the Solitario Canyon Fault on the west, the Bow Ridge Fault on the east, and is dissected by the Ghost Dance and Dune Wash Faults (Figure 2). Topography is pronounced and, north of the central block, is controlled by long, northwest-trending, fault-controlled washes. Within and south of the central block, washes are shorter and trend eastward. Topography in the southern part of Yucca Mountain is controlled by south-trending faults.

6.2 HYDROGEOLOGIC SETTING

The boundaries of the numerical model for saturated-zone flow and transport are shown in Figures 1 and 2, as well as on many subsequent figures. The hydrogeologic setting of the saturated-zone flow system in the vicinity of Yucca Mountain was summarized by Luckey et al. (1996, p. 13). Yucca Mountain is part of the Alkali Flat-Furnace Creek subbasin of the Death Valley groundwater basin, as described by Waddell (1982, pp. 15–16). Discharge within the subbasin occurs at Alkali Flat (Franklin Lake Playa) and, possibly, Furnace Creek in Death Valley (Figure 1). Water inputs to the subbasin include groundwater inflow along the northern boundary of the subbasin, recharge from precipitation in high-elevation areas of the subbasin, and recharge from surface runoff in Fortymile Canyon and Fortymile Wash. North and northeast of Yucca Mountain, recharge from precipitation also probably occurs at Timber Mountain, Pahute Mesa, Rainier Mesa, and Shoshone Mountain (Luckey et al. 1996, p. 13).



DTN: N/A–reference only

NOTE: The blue rectangle is the boundary of the numerical model for saturated zone flow and transport.

Figure 1. Important Physiographic Features Near Yucca Mountain

The saturated volcanic units at Yucca Mountain have been grouped into two confining layers and two aquifers by Luckey et al. (1996, pp. 17–19), based on similarity in their core-scale hydrologic and mechanical properties (Figure 3). In general, the confining units are zeolitic, nonwelded tuffs, and the uppermost aquifers are fractured, welded and devitrified tuffs (the Upper Volcanic Aquifer) or include intervals of fractured, welded and devitrified tuffs (the Lower Volcanic Aquifer). Most zeolite development took place before approximately 11 Ma (Broxton et al. 1987, p. 101; Bish 1989, pp. 31, 33) and was concentrated in the originally permeable, nonwelded vitric tuffs; development was less intense in the partly to densely welded, devitrified tuffs that are present in the interiors of the Prow Pass and Bullfrog Tuffs of the Crater Flat Group. Additionally, alteration to zeolites and clays was more intense and zeolite facies were displaced upward in northern Yucca Mountain because of the high paleotemperature gradients that existed near the calderas (Broxton et al. 1987, pp. 107–108; Bish 1989, p. 35).

Regionally, argillite of the Eleana Formation is a confining layer, and the Paleozoic carbonate rocks are an important aquifer (Winograd and Thordarson 1975, Table 1; Laczniak et al. 1996, Table 1). The Eleana Formation was not intersected by the one borehole drilled deep enough to penetrate it at Yucca Mountain but has been inferred to be present in northern Yucca Mountain based on areal magnetic data (Luckey et al. 1996, p. 20). The carbonate aquifer was penetrated at borehole p#1 (the correspondence between well identifiers and borehole abbreviations is given in Table 2), but its continuity and thickness in this part of southern Nevada, and consequently, its importance as a regional aquifer, may be less near Yucca Mountain than in areas farther to the east (Thomas et al. 1996, Fig. 17).

Average hydraulic conductivities of the hydrogeologic units present at Yucca Mountain were calculated based on single-borehole aquifer-test data summarized in Luckey et al. (1996, Table 4) and are listed in Table 5. Flow logs reported in Luckey et al. (1996, pp. 37–39) indicate that most of the flow in the lower volcanic aquifer is produced by the Prow Pass and Bullfrog Tuffs, with generally lesser amounts produced by other formations. Flow logs for other boreholes (Benson et al. 1983, Figs. 4–6) indicate that variable amounts of water are produced from other formations. The percentages of water contributed to water samples by individual formations based on flow logs conducted during pumping were determined as part of the present analysis and are listed for wells near Yucca Mountain in Table 6.

Water production from boreholes in the northern Amargosa Desert is generally from valley-fill deposits, with the exceptions of the CIND-R-LITE borehole in which production is from the upper volcanic aquifer and borehole TW-5 in which production is from the lower carbonate aquifer (Czarnecki et al. 1997, Fig. 8). The distribution of the different types of valley-fill deposits in the Amargosa Desert is shown by Kilroy (1991, Fig. 3) and includes channel and playa sediments of Holocene age, alluvial fan and freshwater carbonate deposits of Quaternary age, and conglomerates of Tertiary age. Within the model boundary area of Figure 1, Precambrian and Paleozoic clastic and carbonate rocks crop out in the Striped Hills and Skeleton Hills (Claassen 1985, Fig. 1). Alluvium directly south of Yucca Mountain and along the Fortymile Wash drainage is predominantly derived from volcanic rocks, whereas alluvium near Bare Mountain and near the southeast and southwest corners of the model area is predominantly derived from carbonate rocks (Claassen 1985, Fig. 1). Alluvium of mixed lithology is present between these areas. The hydraulic conductivity of the valley fill in the Amargosa Desert is poorly known; Winograd and Thordarson (1975, p. C37, Table 3) reported that valley fill on the NTS had a transmissibility that ranged from 800 to 33,500 gal d^{-1} ft^{-1}, based on the results of pump tests from six boreholes. The saturated hydraulic conductivities calculated by dividing the transmissibilities by the saturated thickness at these boreholes range from 5 to 70 gal d^{-1} ft^{-2} (0.2 to 2.9 m d^{-1}).

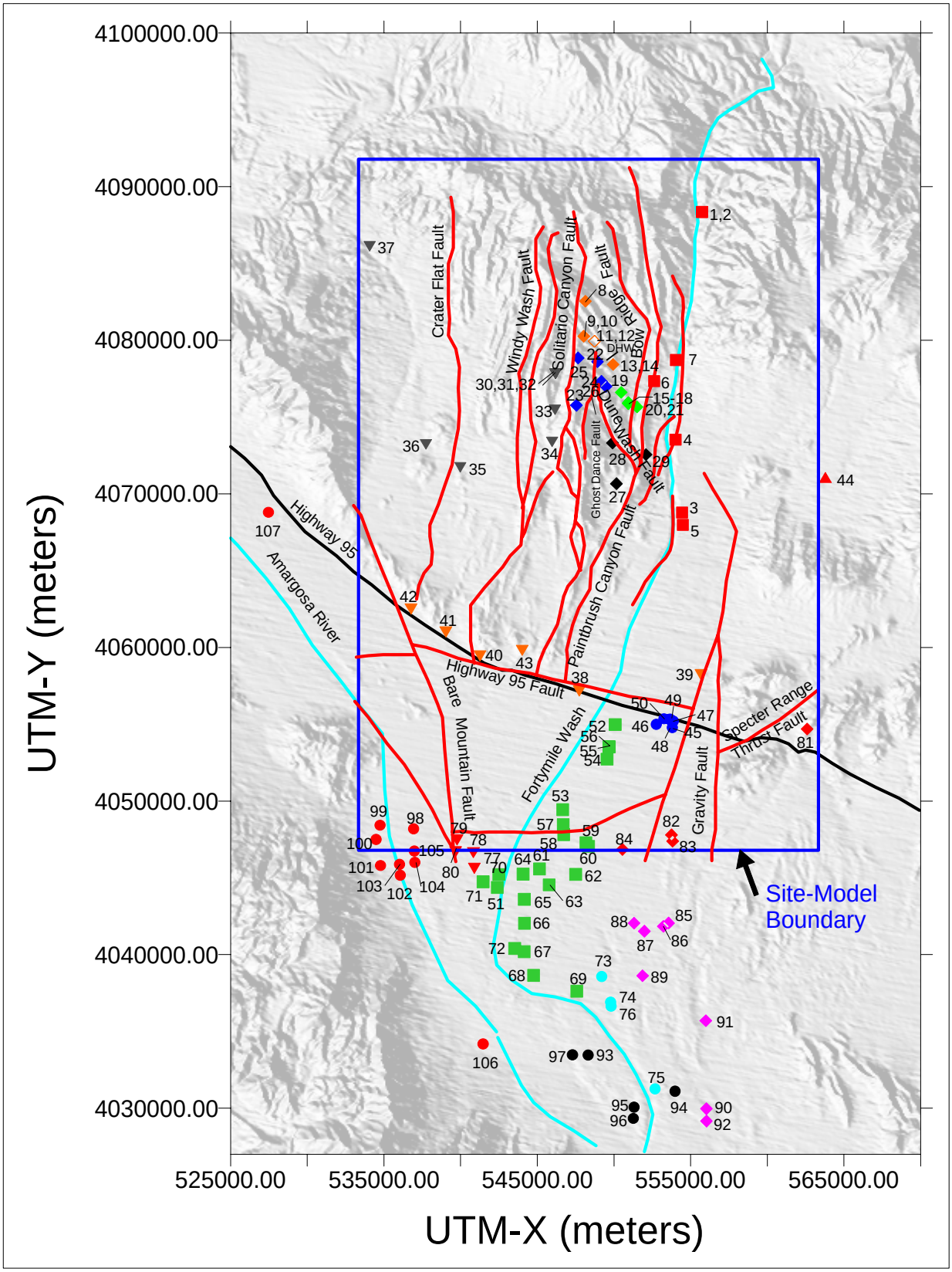


Figure 2. Locations of Boreholes in the Vicinity of Yucca Mountain and the Northern Amargosa Desert (continued on next page)

DTN: GS991208314221.001 (fault locations); MO9907YMP99025.001 and GS920508312321.004 (borehole coordinates)

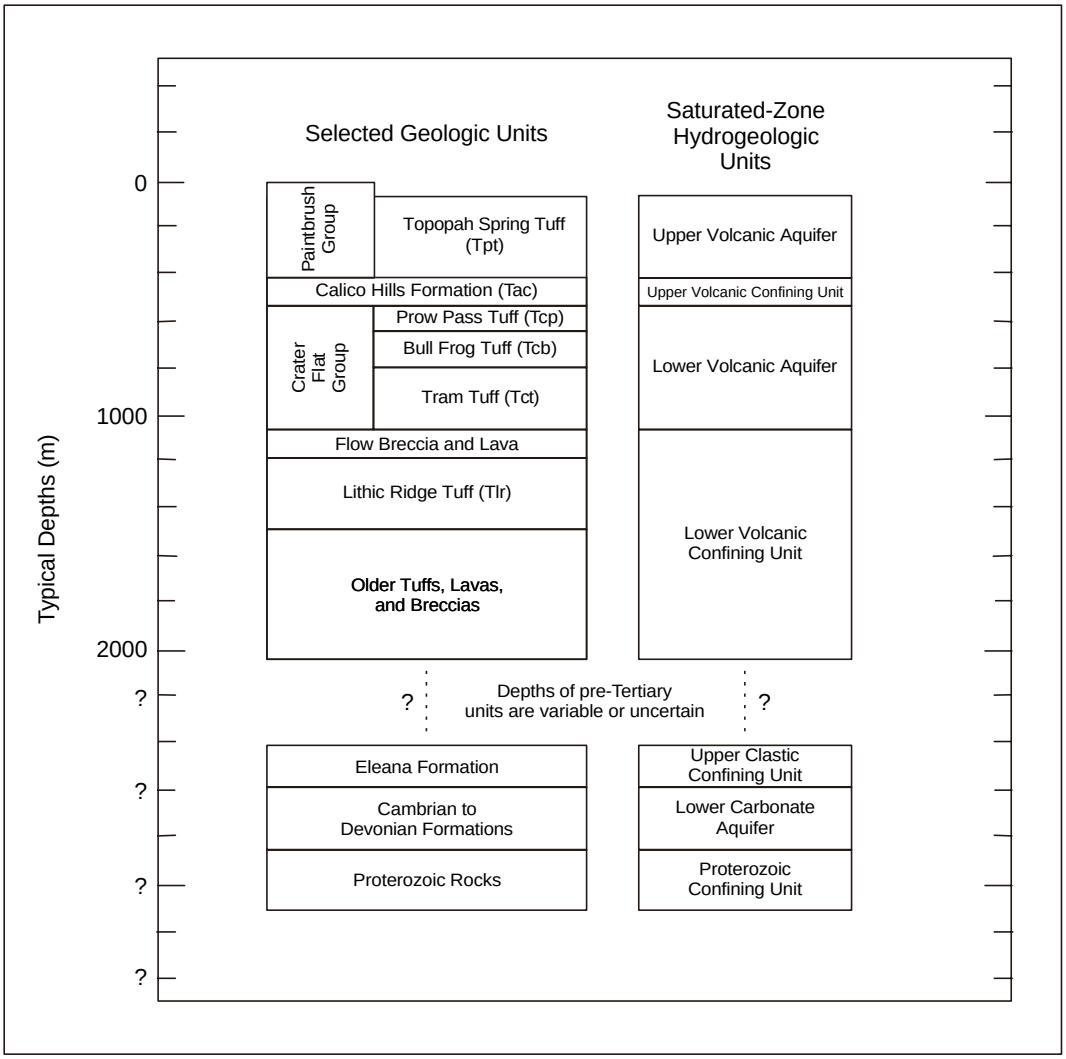
NOTES: See Table 2 for well identifiers

DHW = Drill Hole Wash

Well groupings are discussed in Section 6.5.1.

The figure has color-coded data points and should not be read in a black and white version.

Figure 2 (Continued). Locations of Boreholes in the Vicinity of Yucca Mountain and the Northern Amargosa Desert



DTN: N/A-reference only; Source: Luckey et al. (1996), Fig. 7

NOTE: The explanations for the symbols for the geologic units are given in a footnote to Table 2.

Figure 3. Selected Geologic and Hydrogeologic Units for the Saturated Zone at Yucca Mountain

Table 5. Hydraulic Conductivities of Hydrogeologic Units

Hydrogeologic Unit	Hydraulic Conductivity			Number of Measurements
	Range ($m\ d^{-1}$)	Geometric Mean ($m\ d^{-1}$)	Arithmetic Mean ($m\ d^{-1}$)	
Upper Volcanic Aquifer	1.0	—	—	1
Upper Volcanic Confining Unit	2.0×10^{-2} to 2.6×10^{-1}	8.5×10^{-2}	1.3×10^{-1}	3
Lower Volcanic Aquifer	$< 3.7 \times 10^{-3}$ to 1.4	1.4×10^{-1}	4.3×10^{-1}	10
Lower Volcanic Confining Unit	5.5×10^{-6} to 1.1×10^{-1}	9.1×10^{-4}	1.7×10^{-2}	7
Carbonate Aquifer	1.9×10^{-1}	—	—	1

DTN: N/A-reference only; Source: Luckey et al. (1996), Table 4

Table 6. Percentage of Water Contributed to Water Samples by Individual Formations

	Lower Vol. Confining Unit	Lower Volcanic Aquifer			Upper Vol. Confining Unit	Upper Volcanic Aquifer
Sample	% Lithic Ridge Tuff and older tuffs	% Tram Tuff of Crater Flat Group	% Bullfrog Tuff of Crater Flat Group	% Prow Pass Tuff of Crater Flat Group	% Calico Hills Formation	% Topopah Spring Tuff
J-12	—	—	—	—	0.0	100.0
J-13	0.0	5.0	0.0	0.0	0.0	95.0[a]
JF#3	—	—	—	—	—	100.0
WT#14	—	—	—	—	0.0	100.0[b]
WT#15	—	—	—	—	—	100.0
G-2	0.0	0.0	0.0	0.0	100.0	—
UZ-14 (Tcp)	—	—	0.0	100.0[c]	0.0	—
UZ-14 (Tcb)	—	—	100.0[c]	0.0	0.0	—
H-1 (Tcp)	0.0	0.0	0.0	100.0	0.0	—
H-1 (Tcb)	0.0	0.0	92.0	8.0	0.0	—
b#1 (bh)	—	0.0	49.0	19.0	32.0	—
b#1 (Tcb)	—	0.0	100.0	0.0	0.0	—
c#1	—	36.0	64.0	0.0	0.0	—
c#2	—	0.0	93.0	7.0	0.0	—
c#3	—	25.0	75.0	0.0	0.0	—
c#3 ('95)	—	25.0	75.0	0.0	0.0	—
p#1(v)	35.0	0.5	4.5	58.0	2.0	—
G-4	—	98.5	1.0	0.5	—	—
H-3	10.0	90.0	—	—	—	—
H-4	12.5	32.0	36.5	19.0	—	—
H-5	—	11.0	89.0	—	—	—
UZ#16	—	—	—	100.0	—	—
ONC#1	—	—	—	—	0.0	100.0
WT#12	—	—	—	—	—	100.0[b]
WT-17	—	—	—	100.0	—	—
WT#3	—	—	100.0	—	—	—
H-6(bh)	0.0	34.0	66.0	0.0	—	—
H-6(Tct)	0.0	100.0	0.0	0.0	—	—
H-6(Tcb)	0.0	0.0	100.0	0.0	—	—
WT-7	—	—	—	—	0.0	100.0[b]
WT-10	—	—	—	—	—	100.0

DTN: GS920408312321.002; Sources: Luckey et al. (1996, pp. 37–39); Benson et al. (1983, Figs. 4–6); Thordarson (1983, p. 50).

NOTES: [a]Although borehole J-13 is a deep borehole that extends into the Lithic Ridge Tuff, Thordarson (1983, p. 50) estimated that 95% of the J-13 water sample used in this report originated from the Topopah Spring Tuff between depths of 282.7 to 422.5 m. This estimate was presumably based on the distribution of transmissivity in the borehole, as determined from hydraulic tests in which packers isolated discrete intervals. The transmissivity of the interval of the Topopah Spring Tuff between 282.7 to 422.5 m was 120 $m^2 d^{-1}$, whereas the total transmissivity for the remainder of the borehole was about 5% of this value (Thordarson 1983, p. 55).

[b]Indicates the open, saturated interval of the borehole was in the Topopah Spring Tuff and Calico Hills Formation. The water may have come from anywhere within this interval.

[c]Bailed sample from open borehole (DTN: GS980908312322.008).

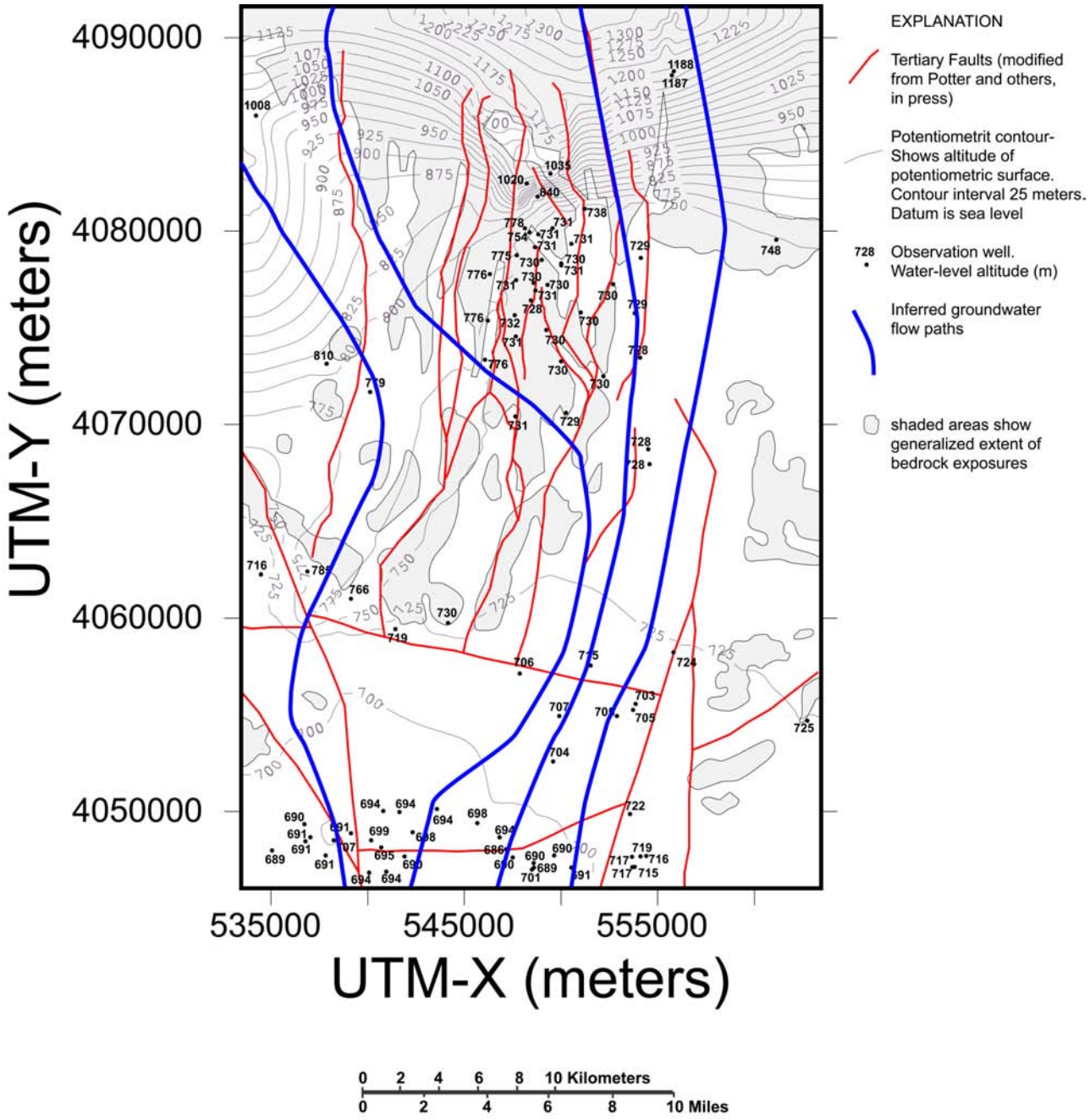
6.3 POTENTIOMETRIC SURFACE

A map of the potentiometric surface in the Yucca Mountain area was developed as part of an associated AMR (USGS 2000, Fig. 1-2) based on average water-level data collected from 1985 to 1995 (Figure 4). The potentiometric-surface elevations at individual boreholes are based on composite water levels in the volcanic units, or at boreholes where heads were measured at multiple depths in the units, on the shallowest head measurement. The water levels have been influenced by local pumping in the southern part of the model area (USGS 2000, p. 4).

Water potential elevations are about 1,030 m at the northern end of the mountain, 810 m at borehole VH-2 in Crater Flat, 730 m beneath much of central Yucca Mountain, and 728 m beneath Fortymile Wash (Tucci and Burkhardt 1995, Fig. 4). The potentiometric heads in the lower monitored intervals of the volcanic units were higher than 775 m at boreholes H-1, H-5, and H-6 and 756.8 m at borehole H-3 (Tucci and Burkhardt 1995, Table 2). The potentiometric head in the carbonate aquifer at p#1 was 752.4 m, indicating that an upward head gradient exists between the carbonate aquifer and the lower volcanic aquifer in this part of Yucca Mountain. In the small-gradient area east and southeast of Yucca Mountain, where the potentiometric surface elevations are between 728 to 732 m, the hydraulic gradient ranges from 0.0001 to 0.0004 (Tucci and Burkhardt 1995, p. 9).

The moderate hydraulic gradient (0.02 to 0.04) (Tucci and Burkhardt 1995, p. 9) across the western boundary of Yucca Mountain was attributed by Luckey et al. (1996, p. 25) to the possible presence of low-permeability fault gouge in the Solitario Canyon Fault or to the juxtaposition of transmissive formations in the hanging block of the fault against less transmissive formations in the footwall side of the fault. An additional but related explanation may be that, as a result of the down-to-the-west displacement in the southern part of Yucca Mountain, the most transmissive parts of the lower volcanic aquifer are locally above the water table immediately east of the Solitario Canyon Fault. The transmissivities of the lower volcanic aquifer at boreholes H-3 and H-5 are $< 1.1\ m^2\ d^{-1}$ and $35\ m^2\ d^{-1}$, values that are low compared to the transmissivities of boreholes east of Yucca Mountain Crest, such as H-4 ($178\ m^2\ d^{-1}$) and G-4 ($589\ m^2\ d^{-1}$) (Luckey et al. 1996, Table 5). The very low transmissivity measured at borehole H-3 may be the result of the near-complete desaturation of the Bullfrog Tuff at this location, whereas the much larger transmissivity at borehole H-5 may be the result of the near-complete saturation of the Bullfrog Tuff.

The cause, and even the existence, of the large hydraulic gradient (0.11) in the northern part of Yucca Mountain have been the subject of considerable debate, as summarized by Luckey et al. (1996, pp. 21, 24, 25). The possible causes include: (1) flow across the thick upper volcanic confining unit; (2) a smaller than average hydraulic conductivity in the lower volcanic aquifer resulting from a combination of hydrothermal alteration and lithostatic pressure; (3) an artifact of attempting to contour heads in two distinct aquifers, the upper and lower volcanic aquifers, separated by a thick confining unit; (4) a graben-bounding fault that drains water from the volcanic aquifer into the carbonate aquifer beneath northern Yucca Mountain, decreasing flow in the volcanic aquifer south of the fault; (5) a graben-bounding fault marks the effective northern limit of the lower volcanic aquifer, due to thinning and alteration of the tuffs of the Crater Flat



DTN: GS991208314221.001 (Tertiary faults); Source: USGS (2000, Fig. 1-2)

NOTE: The inferred groundwater flow paths are based on Assumption 3 in Table 4.

Figure 4. Potentiometric Surface and Inferred Flow Paths (Blue Lines) for Yucca Mountain and Vicinity

Group north of the fault; and (6) the upper clastic confining unit, the Eleana Formation, is buried beneath northern Yucca Mountain and blocks groundwater flow toward the south. Another explanation, not cited by Luckey et al. (1996), is that the potentiometric surface is simply reflecting the large change in ground-surface elevation in the northern part of the Site-Model area.

Explanations 4 through 6 rely extensively on interpretations of magnetic and gravity data. There is no direct surface expression of the postulated graben-bounding fault, nor is there direct evidence from boreholes or outcrop that the Eleana Formation is present in northern Yucca Mountain. However, the transmissivity of the lower volcanic aquifer would be expected to decrease north of Yucca Mountain because of the thinning and disappearance of Bullfrog and Prow Pass Tuffs in the Pinnacles Ridge area (Carr et al. 1986, Figs. 14 and 15). In this case, decreases in head might accompany the increases in transmissivity that result from the greater thicknesses of these units toward the south.

Flow logs for borehole G-2 (Luckey et al. 1996, Fig. 15) provide evidence that the transmissivities of the Bullfrog and Prow Pass Tuffs may be less in the northern part of Yucca Mountain compared to areas further south. These logs show that water inflow during pumping was restricted to the upper volcanic confining unit (the Calico Hills Formation) at this borehole. Pump tests conducted at borehole G-2 in the Calico Hills Formation resulted in an estimated mean transmissivity of 9.4 m^2 d^{-1} (O'Brien 1998, p. 21); however, the natural, predrilling transmissivity at borehole G-2 is probably even less than this value because the Calico Hills Formation may have been hydrofractured by excess downhole fluid pressure applied during drilling (Stock et al. 1985, p. 8691).

Several possible flow paths were defined by drawing flow lines perpendicular to the gradient in the potentiometric surface (Figure 4). The flow paths were drawn under the assumption that hydraulic conductivity and transmissivity are isotropic (Assumption 3 in Table 4). In fractured-rock aquifers, such as those at Yucca Mountain, hydraulic conductivity probably is anisotropic (Luckey et al. 1996, p. 36). However, Czarnecki and Waddell (1984, pp. 27–28 and Table 4) reported that their subregional model duplicated measured water levels more accurately when the aquifer was simulated as isotropic rather than anisotropic. Therefore, this assumption provides a reasonable basis for evaluating the possible sources and destinations of groundwater in the Yucca Mountain area. Groundwater models of the site that account for the effects of faults and anisotropy on the flow paths may indicate paths substantially different than those drawn in Figure 4.

The flow paths shown in Figure 4 indicate that water may flow under Yucca Mountain predominantly from the northwest. In Figure 4, some of the flow from the north is predicted to be diverted southeastward toward Fortymile Wash in northern Yucca Mountain, an area dominated by northwest-trending, fault-controlled washes. The inferred flow lines indicate that groundwater flows southeast from Yucca Mountain and southwest from Jackass Flats toward the Fortymile Wash area. Groundwater from the Fortymile Canyon area flows south and then southwest in the southern part of the Site-Model Area. Flow in the southern part of Yucca Mountain is predominantly southeastward toward Fortymile Wash rather than south toward the Amargosa Desert (Figure 4). The faults in the southern part of Yucca Mountain do not seem to exert an observable effect on the potentiometric surface, but this lack of evidence could simply be due to the sparseness of boreholes and shallowness of the hydraulic gradient in this area.

6.4 PREVIOUS WORK

Yucca Mountain has been under investigation as a potential repository site since the early 1980s, and an extensive body of literature exists concerning its hydrologic and geologic characteristics. The following summary of that literature is not exhaustive but represents the range of interpretations that have been made concerning groundwater flow at and near Yucca Mountain.

6.4.1 Data Sources

Many of the geochemical and isotopic data for Yucca Mountain discussed in this report were first presented in Benson et al. (1983, Table 1), Ogard and Kerrisk (1984, Tables I, II, V, and VI), and Benson and McKinley (1985, Table 1). Benson et al. (1983, Figs. 4, 5, and 6) also provided data on the depths of water-producing zones in the wells that produced the groundwater samples. Additional hydrochemical and isotopic data from the regional groundwater system were obtained from relatively shallow wells drilled to monitor water table depths and from unsaturated-zone test wells that reached the water table.

Benson et al. (1983, p. 16) and Luckey et al. (1996, p. 43) cautioned that the high lithium concentrations and the presence of foam in some of the groundwater samples indicated that these samples contained air-foam drilling fluids to which lithium bromide had been added as a tracer. These comments referred primarily to samples collected at water-table (WT) boreholes but may also apply to samples collected at unsaturated-zone test holes that reached the water table. Based on the lithium concentrations of the water samples, Benson et al. (1983, p. 16) estimated that the percentage of drilling fluid in the samples was generally much less than 1%; however, lithium readily sorbs to rock, so the lithium concentrations may be an unreliable indicator of remnant drilling fluid in the samples (see Assumption 2 in Table 4).

Pore- and perched-water data from the unsaturated zone at Yucca Mountain were reported by Yang et al. (1996, Tables 2–4, 6, 7) and Yang et al. (1998, Tables 2–4, 6, 9–13, 15–17). Milne et al. (1987, Tables 3 and 5) and Ingraham et al. (1991, Tables 1 and 2) discussed delta deuterium (δD) and delta oxygen-18 ($\delta^{18}O$) values of modern precipitation in southern Nevada. Hydrochemical and isotopic data for the Amargosa Desert were reported by Claassen (1985, Tables 1 and 6) and by McKinley et al. (1991, Table 2). Additional hydrochemical data for much of the NTS were summarized in McKinley et al. (1991, Table 6), data for the Death Valley Region were summarized by Perfect et al. (1995, attached *dataedit.exe* data file), and data for Nye County were compiled by Oliver and Root (1997, attached *yucca.xls* data file).

6.4.2 Interpretations of Flow Patterns in the Vicinity of Yucca Mountain from Hydrochemical and Isotopic Data

Over the past ten years, several published studies (White and Chuma 1987; Benson and Klieforth 1989; Stuckless et al. 1991; Fridrich et al. 1994; Luckey et al. 1996; Campana and Byer 1996) have focused on the origin and flow paths of groundwater in the vicinity of Yucca Mountain. These authors primarily differed with respect to the extent of recharge occurring through Yucca Mountain or along Fortymile Wash, the residence time of groundwater beneath Yucca Mountain, and the extent of mixing between the volcanic and carbonate aquifers.

Based on δD and $\delta^{18}O$ data for the Yucca Mountain region, Benson and Klieforth (1989, p. 48) proposed that groundwater beneath Yucca Mountain could be a mixture of overland flow along Fortymile Wash and groundwater flow from upland areas to the north (Pahute Mesa). Benson and Klieforth (1989, pp. 48–49, Fig.11) reported that the $\delta^{18}O$ values of groundwater in the vicinity of Yucca Mountain were higher for water with apparent ^{14}C ages between 18.5 and 9 ka (thousand years before present) and were lower and constant since then, a relation that was attributed to global climate change and accompanying changes in the paths of storms bringing moisture to southern Nevada prior to 9 ka. Benson and Klieforth (1989, p. 42) also argued that groundwater ^{14}C ages in the Yucca Mountain area do not require substantial correction to account for the dissolution of calcite, based on geochemical modeling of three wells in Fortymile Wash by White and Chuma (1987, Table 2, Fig. 23) and the observation that surface runoff in Fortymile Wash was saturated with calcite and yet still had a ^{14}C activity of 100 percent modern carbon (pmc).

Groundwater in the volcanic aquifers in the Yucca Mountain area was interpreted by Stuckless et al. (1991, p. 1414) to be a mixture of at least three end members. One source of groundwater in the volcanic aquifer, represented by groundwater from borehole UE-29 a#2 in Fortymile Canyon, is characterized by isotopically light carbon-13 ($\delta^{13}C$), a high carbon-14 (^{14}C) activity, and isotopically heavy δD. This groundwater is either mixed with groundwater from the Paleozoic carbonate aquifer having an isotopically heavy $\delta^{13}C$ and a low ^{14}C activity, or alternatively, is modified by calcite derived from the carbonate aquifer with these isotopic characteristics. A third, poorly constrained end member with a $\delta^{13}C$ value and ^{14}C activity intermediate between that of the first and second sources and having a lighter δD value than the first source was hypothesized to explain the scatter in the $\delta^{13}C$ and ^{14}C about a possible mixing trend line (Stuckless et al. 1991, Fig. 4). Groundwater at Pahute Mesa from borehole UE-20 a#2 has these characteristics and was suggested by Stuckless et al. (1991, p. 1414) as a possible third source for the groundwater at Yucca Mountain.

Fridrich et al. (1994, pp. 153–159) used the spatial variability in $\delta^{13}C$, water-table temperature, magnetic data, and unsaturated-zone heat flux to infer that groundwater in the northern part of Yucca Mountain entered the deep carbonate aquifer and reemerged into the shallow volcanic aquifer along faults in the central and southern parts of the mountain. Luckey et al. (1996, p. 44) noted the downgradient increase in the calcium-to-sodium ratio from west to east across Yucca Mountain and speculated that it might reflect either upwelling from the underlying carbonate aquifer through faults on the east side of Yucca Mountain or mixing of water flowing from the west with calcium-rich water recharged from Fortymile Wash.

Campana and Byer (1996, p. 465) presented a steady-state mixing-cell model of the NTS regional groundwater flow system that used corrected ^{14}C ages to determine flow volumes and directions and recharge rates in the regional flow system. Their results indicated that between 28 and 88% of the groundwater beneath Yucca Mountain originated as local recharge, which was estimated to be between 1.9 to 4.2 mm yr^{-1} as an annual average distributed evenly across the cell's surface area (Campana and Byer 1996, p. 473). In their model, the remainder of the flow beneath Yucca Mountain originated from the west in Crater Flat. Flow from upland areas north of Yucca Mountain was diverted eastward toward Fortymile Canyon and Fortymile Wash before reaching Yucca Mountain. Groundwater beneath Yucca Mountain was interpreted by Campana and Byer (1996, Fig. 5) to be a mixture of groundwaters having different ^{14}C activities, with a

mean age of 10.9 to 16.0 ka and a median age of 6.3 to 6.5 ka (Campana and Byer 1996, Table 7). Approximately 20 to 25% of the total recharge in their regional model domain originated from the Fortymile Canyon and Wash area, where areally distributed recharge rates were estimated to be 26 to 32 mm yr^{-1} (5.3 x 10^6 to 6.6 x 10^6 m^3 yr^{-1}) (Campana and Byer 1996, p. 476). Water in the Amargosa Desert originated from groundwater flow from Fortymile Canyon and Wash area and Crater Flat.

6.4.3 Origin of Water in the Amargosa Desert

Winograd and Thordarson (1975, p. C111) concluded from chemical data that groundwater in the central Amargosa Desert (Figure 1) originates from at least three sources: (1) water dominated by calcium, magnesium, sodium, and bicarbonate that flows across the hydraulic barrier responsible for springs at Ash Meadows; (2) water southwest of Amargosa Valley (formerly, Lathrop Wells) dominated by sodium, potassium, and bicarbonate that probably flows from western Jackass Flats; and (3) water in the west-central and northwestern Amargosa Desert that flows from Oasis Valley. In addition, Winograd and Thordarson (1975, p. C112) noted the dilute nature of the groundwater near Fortymile Wash and interpreted the low dissolved solids content of this water to indicate an origin from paleorecharge along the channel rather than underflow from areas north of Jackass Flats. Winograd and Thordarson (1975, p. C112) also noted the higher dissolved solids content in wells at and south of Amargosa Valley, which they attributed to small amounts of groundwater leaking upward from the carbonate aquifer into the valley fill near the Gravity Fault.

Claassen (1985) and White and Chuma (1987) presented different hypotheses regarding the origin of water in the northern Amargosa Desert near the present-day Fortymile Wash drainage. Claassen (1985, p. F30) argued that groundwater near surface drainages was predominantly derived from surface runoff during the Pleistocene and the very early Holocene based on its apparent ^{14}C age (Claassen 1985, Fig. 15) and on the high ratio of calcium plus magnesium to sodium plus potassium [$(Ca^{2+} + Mg^{2+})/(Na^{+} + K^{+})$] of groundwater from the northern Amargosa Desert compared to groundwater from upgradient locations (Claassen 1985, p. F13, Fig. 9). In contrast, White and Chuma (1987, p. 578) argued that groundwater in the northern Amargosa Desert evolved chemically from groundwater that had recharged upgradient in Fortymile Canyon. The ^{14}C age of groundwater in the northern Amargosa was used to calculate groundwater velocities beneath Fortymile Wash of between 3 and 30 m yr^{-1} over an average distance of about 15 km extending southward from borehole J-13 to the north-central Amargosa Desert (White and Chuma 1987, p. 578).

6.4.4 Numerical Flow Models

Numerical models of flow in the Yucca Mountain region include those by Czarnecki and Waddell (1984, Plate 2) and Czarnecki (1984, p. 1). In the models of Czarnecki and Waddell (1984, Plate 2) and Czarnecki (1984, Fig. 14), groundwater recharged in Fortymile Canyon flowed around a low-permeability barrier (assumed to cause the large hydraulic gradient in the northern part of Yucca Mountain) and under Yucca Mountain from the west and northwest. From the potential repository area of Yucca Mountain, groundwater flowed south-southeast and then southwest into the northern Amargosa Desert. Czarnecki and Waddell (1984, p.12 (model variable *Qfm*) and p. 20) estimated recharge beneath Fortymile Wash and Canyon to be 2.2 x 10^4 m^3 d^{-1} (8.0 x 10^6 m^3 yr^{-1}) based on a trial-and-error fit of the model to measured water-level data.

This volume of water corresponded to an average recharge rate of 41 mm yr^{-1} for the model area corresponding to Fortymile Wash and Canyon (Czarnecki 1984, p. 5). Czarnecki (1984, p. 18) used the same recharge rate for the Fortymile Wash and Canyon area in his model and assumed an areally distributed recharge rate of 0.5 to 2.0 mm yr^{-1} in the vicinity of Yucca Mountain.

Sensitivity analyses by Czarnecki (1984, p. 21) investigated the possible effects of increased recharge rates that might occur under a wetter climate with twice the annual precipitation of the present climate. These analyses indicated that a 130-m water-table rise and an increase in groundwater flux by a factor of 2 to 4 could be expected beneath the potential repository area during such a climate (Czarnecki 1984, p. 32). Flow directions simulated for the wetter climate were similar to those simulated for the present climate (Czarnecki 1984, Figs. 14 and 15). However, this conclusion may have resulted from the two-dimensional nature of the model and the model assumptions regarding the cause of the large hydraulic gradient in the northern part of Yucca Mountain.

D'Agnese et al. (1997, Figs. 1 and 32) presented a model of flow in the Death Valley region that included Yucca Mountain; however, because of its very large areal extent, the model lacks the detail near Yucca Mountain provided by the earlier models. Generalized flow vectors based on the model show groundwater from the north flowing west of Yucca Mountain beneath Crater Flat and east of Yucca Mountain beneath Fortymile Canyon (D'Agnese et al. 1997, Fig. 32).

6.4.5 Fortymile Wash Recharge

In addition to the recharge estimates for Fortymile Wash made by Czarnecki and Waddell (1984, p. 12) through numerical flow modeling (8.1×10^6 m^3 yr^{-1}) (Section 6.4.4) and by Campana and Byer (1996, p. 476) through hydrochemical mixing models (5.3×10^6 to 6.6×10^6 m^3 yr^{-1}) (Section 6.4.2), recharge estimates for various reaches of Fortymile Wash were also made by Savard (1998, p. 20) based on channel-volume losses during runoff and an assumed inversely proportional relationship between these volume losses and recharge. Long-term groundwater recharge rates were 27,000 m^3 yr^{-1} for Fortymile Canyon, 1,100 m^3 yr^{-1} for upper Jackass Flats, 16,400 m^3 yr^{-1} for lower Jackass Flats, and 64,300 m^3 yr^{-1} for the Amargosa Desert (Savard 1998, p. 1). Adding these values, the total recharge estimated for Fortymile Canyon and Fortymile Wash by Savard (1998) is 1.1×10^5 m^3 yr^{-1}, or 1.3% of the 8.1×10^6 m^3 yr^{-1} used in the models of Czarnecki and Waddell (1984, p. 12) and Czarnecki (1984, p. 18), or about 0.6 mm yr^{-1}, assuming the same area for Fortymile Canyon and Wash that was used in those models.

6.5 ANALYSIS OF HYDROCHEMICAL AND ISOTOPIC DATA

This section presents the results of the analysis of the hydrochemical and isotopic data in the vicinity of Yucca Mountain in seven major subsections. Subsection 6.5.1 presents areal distribution maps showing values measured for chemical and isotopic constituents in groundwater samples from wells in the vicinity of Yucca Mountain (data for these plots are listed in Table 3). Subsection 6.5.2 presents an analysis of groundwater flow paths in the Yucca Mountain region based on these distribution maps. Subsection 6.5.3 presents an evaluation of the evidence regarding local recharge at Yucca Mountain. An evaluation of the evidence for the timing of recharge is presented in Subection 6.5.4. Evidence for mixing relations among groundwaters is discussed in Subection 6.5.5. Section 6.5.6 reviews geochemical and isotopic evidence for the magnitude of recharge at Yucca Mountain. Evidence for downgradient dilution of chemical constituents in groundwaters from Yucca Mountain is evaluated in Subection 6.5.7.

6.5.1 Areal Distributions of Chemical and Isotopic Species

In this subsection, areal distributions of values measured for the concentrations of major cations and anions and for isotopic ratios are presented, along with some preliminary analysis. The discussions of areal trends in individual chemical and isotopic constituents are intended to be somewhat general in character.

The locations of wells cited in this section are shown in Figure 2. As the figure shows, areal coverage is somewhat uneven, with many wells located at Yucca Mountain and in agricultural areas in the Amargosa Desert but with far fewer wells elsewhere in the map area. Data are particularly scarce in the eastern and northern parts of the map area and in the southern part of Yucca Mountain, north of the Nye County Early Warning Detection Program (NC-EWDP) wells. Consequently, the extent to which the available data are representative for these areas is difficult to assess (Assumptions 1 and 2 in Table 4).

The boreholes shown in Figure 2 and listed in Table 2 generally could be grouped by geographic area or by association with particular features, such as Fortymile Wash or the Gravity Fault, or by hydrochemical signature. Each group of boreholes is identified by a unique symbol and color, which are used in plots presented in later sections. The use of different symbols in the plots allows the differences (or similarities) in the concentrations of chemical and isotopic species to be more easily distinguished. The basis for grouping the boreholes in the manner shown in Figure 2 is largely self-explanatory, but some further explanation for particular groups follows.

Boreholes at Yucca Mountain were divided into (1) a northern group (YM-N), which includes boreholes along and north of Drillhole Wash, (2) an eastern group (YM-E) including borehole p#1, which extends to the carbonate aquifer, (3) a central group (YM-C), which includes boreholes located within the central block of Yucca Mountain, as defined by Day et al. (1998, p. 1, Map I-2601), and (4) a southern group (YM-S), which includes boreholes along and south of Dune Wash.

Boreholes in the Crater Flat group (CF) include boreholes WT-10, WT-7, and H-6, which are located near Yucca Mountain but west of the Solitario Canyon Fault. Existing boreholes drilled as part of the NC-EWDP are generally located along the southern edge of Crater Flat, except for borehole NC-EWDP-5S, which is east of Fortymile Wash in southern Jackass Flats. The NC-EWDP boreholes are grouped together with the CIND-R-LITE borehole into a single group (NC-EWDP) despite the lack of association with a single geographic or hydrologic feature.

Boreholes near Fortymile Wash were divided into a northern group (FMW-N), which includes the boreholes east and northeast of Yucca Mountain, and a southern group (FMW-S), which includes the boreholes between or along the main channels of Fortymile Wash in the Amargosa Desert, as shown in Claassen (1985, Fig. 3). Boreholes in the Amargosa Desert located to the east and west of the distributary channels of Fortymile Wash but not associated with other hydrologic or geographic features are included in the groups FMW-E and FMW-W, respectively.

The Jackass Flats (JF) group consists of a single borehole (J-11), located in central Jackass Flats. The boreholes located near the community of Amargosa Valley are in the group LW. Boreholes near the Skeleton Hills and Specter Range Thrust Fault are grouped together (SH), as are boreholes located farther south near the Gravity Fault (GF). The Amargosa River group (AR) includes boreholes located near the southwest corner of the Site Model, the NEC Well west of Bare Mountain, and borehole 27N/4E-27bbb in California. Boreholes located near the

confluence of the Amargosa River and Fortymile Wash drainages are grouped together (AR/FMW). This group does not include site 17S/49E-35ddd (Ash Tree Spring), which is included in the FMW-E group.

6.5.1.1 Chloride

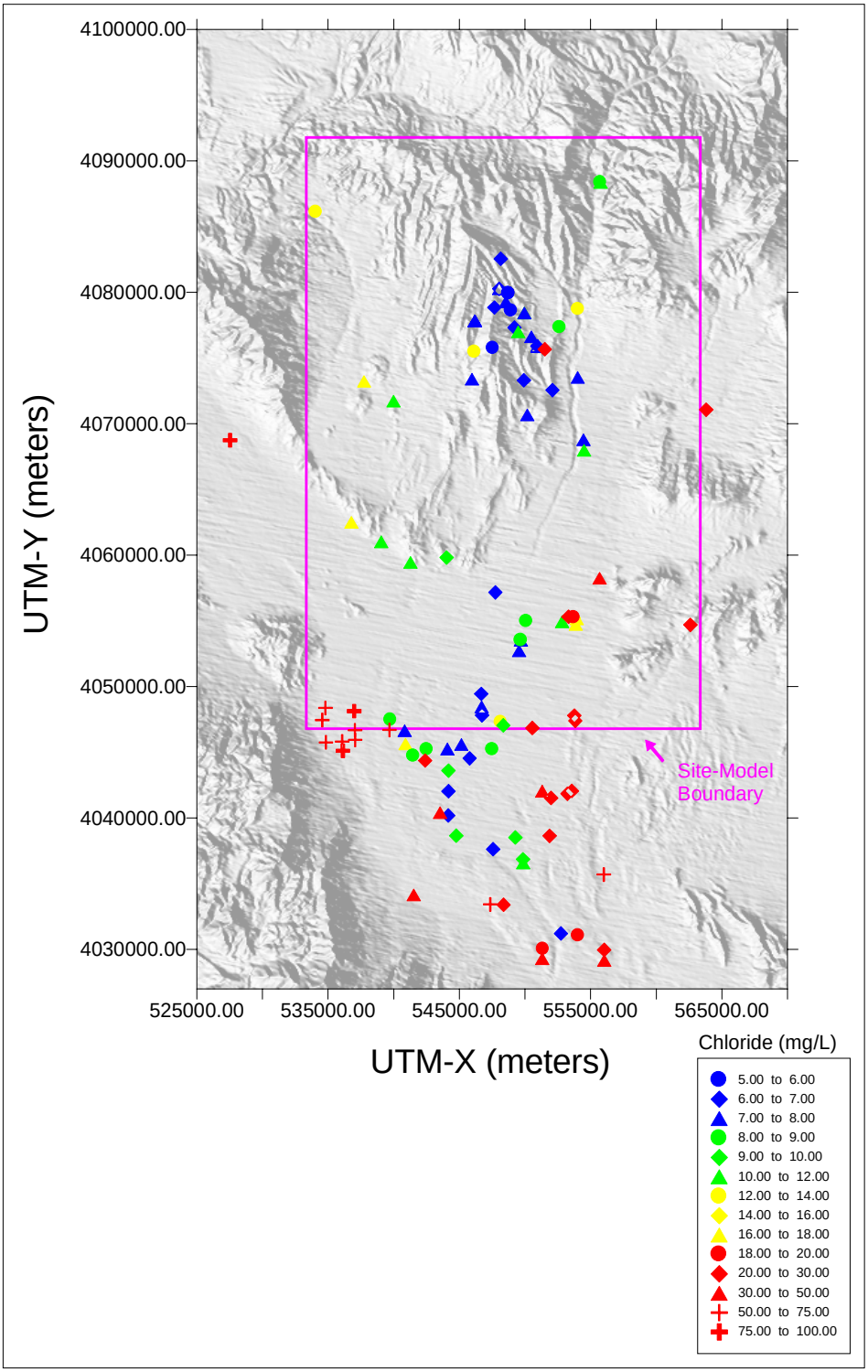
The chloride (Cl^-) concentrations of groundwater samples in the Yucca Mountain vicinity are shown in Figure 5. The areal distribution clearly shows spatial zonations in Cl^- concentrations. Except for borehole p#1, where groundwater was sampled from the carbonate aquifer and from deep in the volcanic section where groundwater seems to be mixed with groundwater from the carbonate aquifer, the Cl^- concentrations of groundwater in the Yucca Mountain area generally are low (less than 9 mg L^{-1}) compared to areas to the west and east. Although few data are available, groundwater in eastern Crater Flat has low Cl^- concentrations compared to groundwater in western Crater Flat, a distinction that is preserved at the south end of Crater Flat at the NC-EWDP boreholes. Low Cl^- concentrations associated with the Fortymile Wash area east of Yucca Mountain extend southward into the Amargosa Desert, where the low-concentration zone is bounded by areas having substantially higher Cl^- concentrations. Groundwater near the southwest corner of the Site-Model boundary has Cl^- concentrations in excess of 50 mg L^{-1}, as does the single sample from the NEC Well in the hydraulically upgradient area west of Bare Mountain.

6.5.1.2 Sulfate

The areal distribution of sulfate (SO_4^{2-}) (Figure 6) has patterns similar to those described for Cl^- (Figure 5). Except at borehole p#1 where the SO_4^{2-} concentrations are much higher, groundwater at Yucca Mountain generally has SO_4^{2-} concentrations less than 35 mg L^{-1}, whereas SO_4^{2-} concentrations west and east of Yucca Mountain are moderately to substantially higher. Borehole J-11 in central Jackass Flat has a SO_4^{2-} concentration of 449 mg L^{-1}. The compositional differences between groundwater in western and eastern Crater Flat are also evident in SO_4^{2-} concentrations, with the difference that the SO_4^{2-} concentration at Gexa Well 4 in the northwest corner of the Site-Model Area more closely resembles groundwater in eastern (VH-1) rather than western (VH-2) Crater Flat. As is the case for Cl^-, the low SO_4^{2-} groundwater associated with Fortymile Wash east of Yucca Mountain also extends southward into the Amargosa Desert, where it is surrounded by groundwater having distinctly higher SO_4^{2-} concentrations. The groundwater with high Cl^- concentrations near the southwest corner of the Site-Model Area also has relatively high (100 to 200 mg L^{-1}) SO_4^{2-} concentrations. Groundwater north and northwest of this area has similarly high SO_4^{2-} concentrations.

6.5.1.3 Bicarbonate

The areal distribution of bicarbonate (HCO_3^-) is shown in Figure 7. The areal patterns for HCO_3^- are similar to those described for SO_4^{2-} and Cl^- with some differences. Groundwater with high (greater than 200 mg L^{-1}) HCO_3^- concentrations is present in easternmost Crater Flat and western Yucca Mountain near Solitario Canyon. Elsewhere at Yucca Mountain, groundwater generally has HCO_3^- concentrations less than 175 mg L^{-1}. Groundwater in central Jackass Flats at borehole J-11, where the high SO_4^{2-} was noted previously, has one of the lowest HCO_3^- concentrations (102 mg L^{-1}) in the map area. Groundwater near the Fortymile Wash drainage in the Amargosa Desert has much lower (less than 160 mg L^{-1}) HCO_3^- concentrations than groundwater in the surrounding areas but has slightly higher HCO_3^- concentrations than groundwater upgradient along Fortymile Wash.



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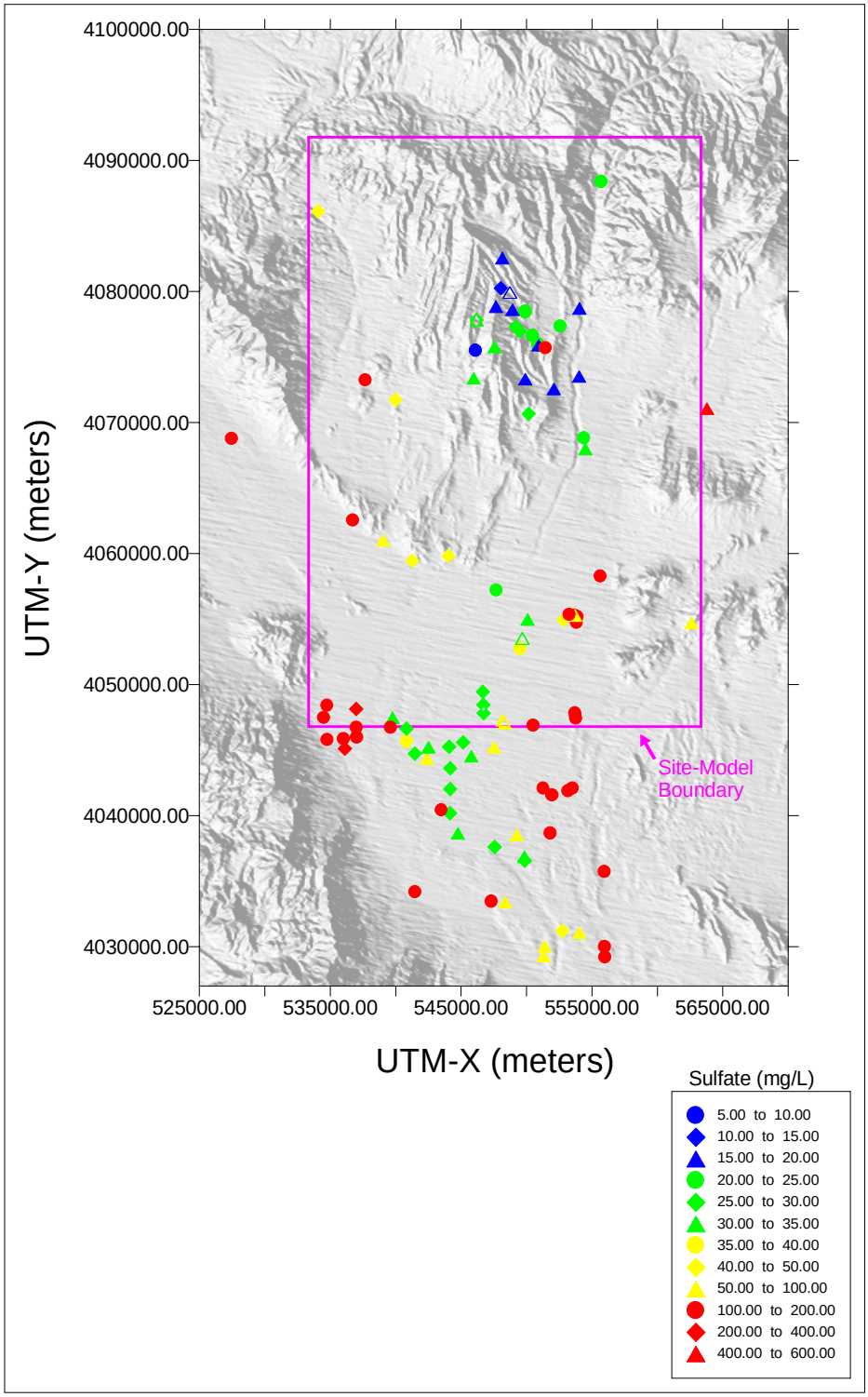
NOTE: This figure has color-coded data points and should not be read in a black and white version.

Figure 5. Areal Distribution of Chloride in Groundwater



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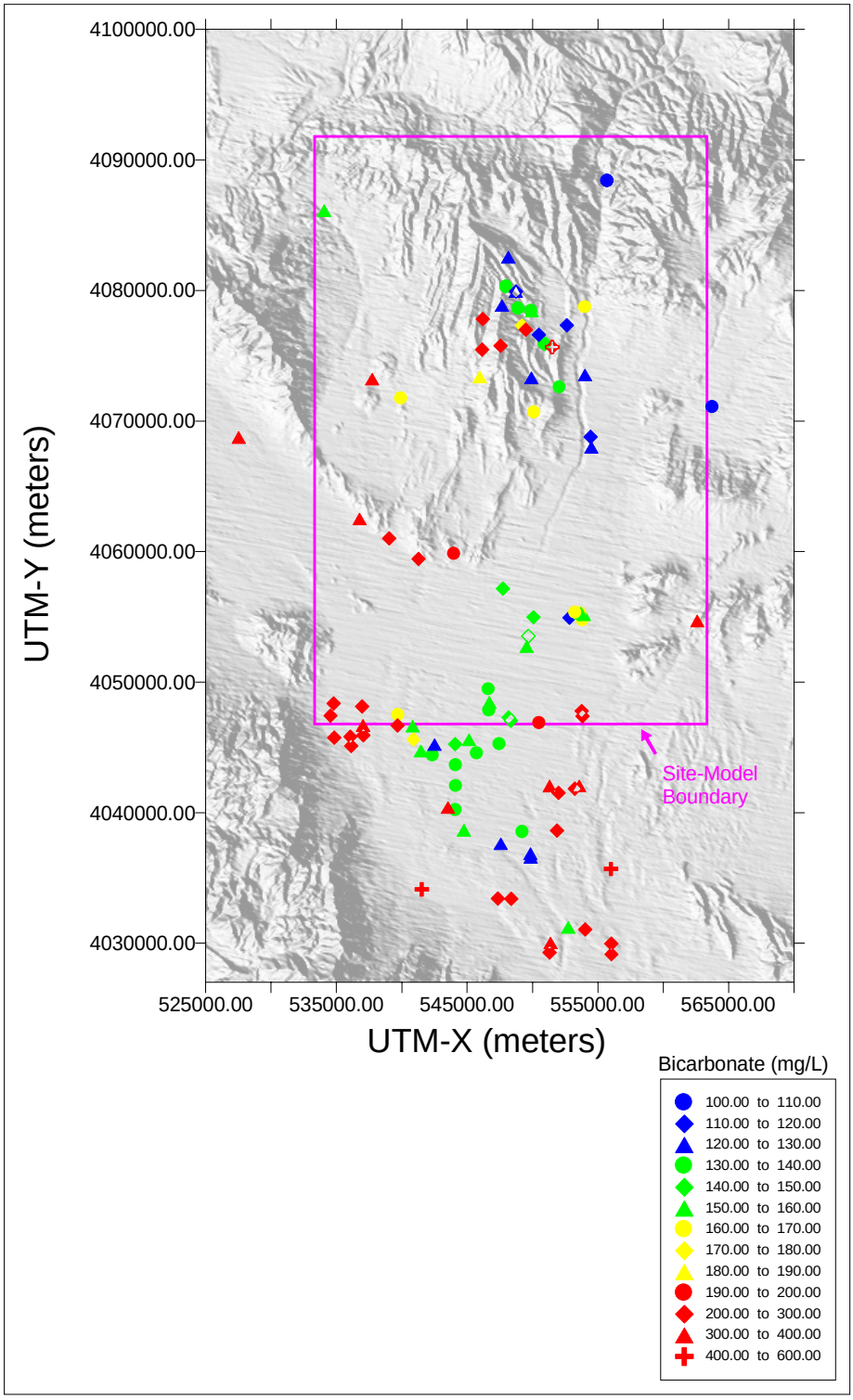
NOTE: This figure has color-coded data points and should not be read in a black and white version.

Figure 6. Areal Distribution of Sulfate in Groundwater



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NOTE: This figure has color-coded data points and should not be read in a black and white version.

Figure 7. Areal Distribution of Bicarbonate in Groundwater

6.5.1.4 Calcium

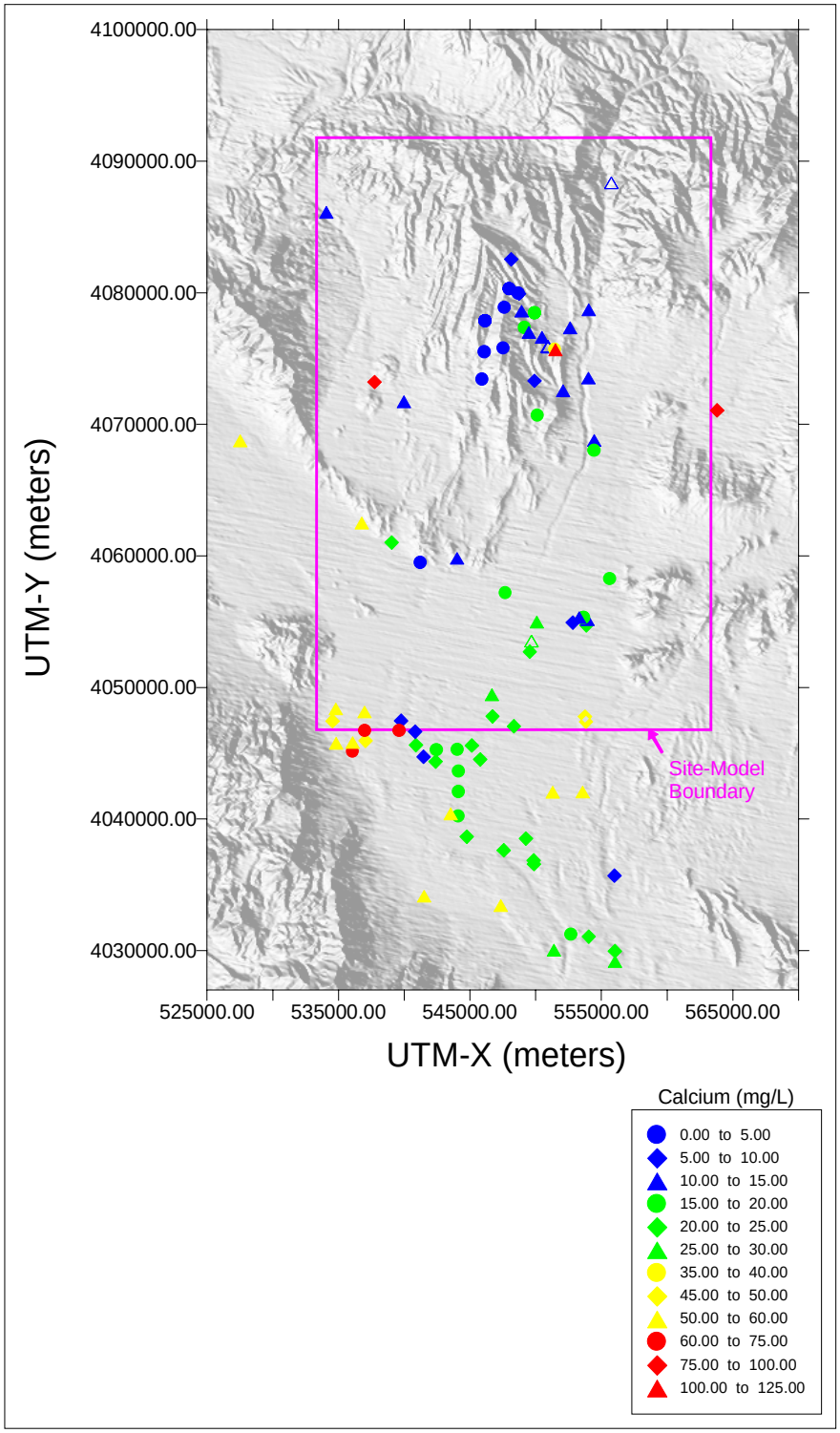
The calcium (Ca^{2+}) concentrations of groundwater at Yucca Mountain are generally less than 20 mg L^{-1} (Figure 8), except at borehole p#1 where groundwater from the carbonate aquifer has a concentration of 100 mg L^{-1}. Along the eastern edge of Crater Flat and in western Yucca Mountain, Ca^{2+} concentrations are less than 5 mg L^{-1}. The Ca^{2+} concentration is higher in western Crater Flat at borehole VH-2 than in eastern Crater Flat at borehole VH-1. The Ca^{2+} concentration at Gexa Well 4 in the northwest corner of the Site-Model Area is similar to the value at VH-1 and at NC-EWDP wells southeast of Crater Flat. The Ca^{2+} concentration is relatively high (82 mg L^{-1}) at borehole J-11 in central Jackass Flats, where SO_4^{2-} is also relatively high (Figure 6). The Ca^{2+} concentration along Fortymile Wash is between 10 to 20 mg L^{-1} east and northeast of Yucca Mountain and increases to values generally between 20 to 30 mg L^{-1} in the Amargosa Desert. The Ca^{2+} concentration increases to either side of Fortymile Wash in the Amargosa Desert. Groundwater Ca^{2+} concentrations in the southwest corner of the Site-Model Area are similar to the Ca^{2+} concentrations in upgradient areas in western Crater Flat and west of Bare Mountain.

6.5.1.5 Magnesium

The areal distribution of magnesium (Mg^{2+}) (Figure 9) shows that Mg^{2+} concentrations in groundwater at Yucca Mountain range from 0.1 to 1.6 mg L^{-1}, except at borehole p#1 where the Mg^{2+} concentration is 10 mg L^{-1} in the volcanic aquifer and 39 mg L^{-1} in the carbonate aquifer. The Mg^{2+} concentration in groundwater in western Crater Flat at borehole VH-2 is high (30 mg L^{-1}) compared to groundwater at borehole VH-1 (1.5 mg L^{-1}). In NC-EWDP wells south of Crater Flat, Mg^{2+} concentrations range from less than 1 to 31 mg L^{-1}, with concentrations generally increasing to the west. Concentrations of Mg^{2+} are low (0.2 mg L^{-1}) at the northernmost borehole along Fortymile Wash (a#2) but are generally between 2 and 3 mg L^{-1} along the length of Fortymile Wash east of Yucca Mountain and in the Amargosa Desert. In the eastern part of the Amargosa Desert near Amargosa Valley, Mg^{2+} concentrations can be both higher and lower than in groundwater near the adjacent reach of Fortymile Wash. South of the southern boundary of the Site Model near the Gravity Fault, Mg^{2+} concentrations are generally between 5 and 20 mg L^{-1}. In the southwest corner of the model area, Mg^{2+} concentrations generally are between 5 to 10 mg L^{-1}, but a few samples have concentrations between 10 and 20 mg L^{-1}, similar to the concentration of groundwater at the NEC Well west of Bare Mountain (14 mg L^{-1}). The concentration of Mg^{2+} is 13 mg L^{-1} at borehole J-11 in central Jackass Flats.

6.5.1.6 Sodium

The areal distribution of sodium (Na^{+}) is shown in Figure 10. Excluding data from the carbonate aquifer (borehole p#1), the Na^{+} concentrations of groundwater at Yucca Mountain range between 46 and 120 mg L^{-1}. The values toward the high end of this range are generally in the western part of Yucca Mountain and are similar to values along the eastern edge of Crater Flat. The Na^{+} concentrations of groundwater in the NC-EWDP boreholes west of Fortymile Wash are generally between 40 and 80 mg L^{-1}, except at borehole NC-EWDP-3D where the Na^{+} concentration was anomalously high (113 mg L^{-1}). The Na^{+} concentrations of groundwater at borehole NC-EWDP-55 west of the Striped Hills and at J-11 in central Jackass Flats are also high (149 and 143 mg L^{-1}, respectively).



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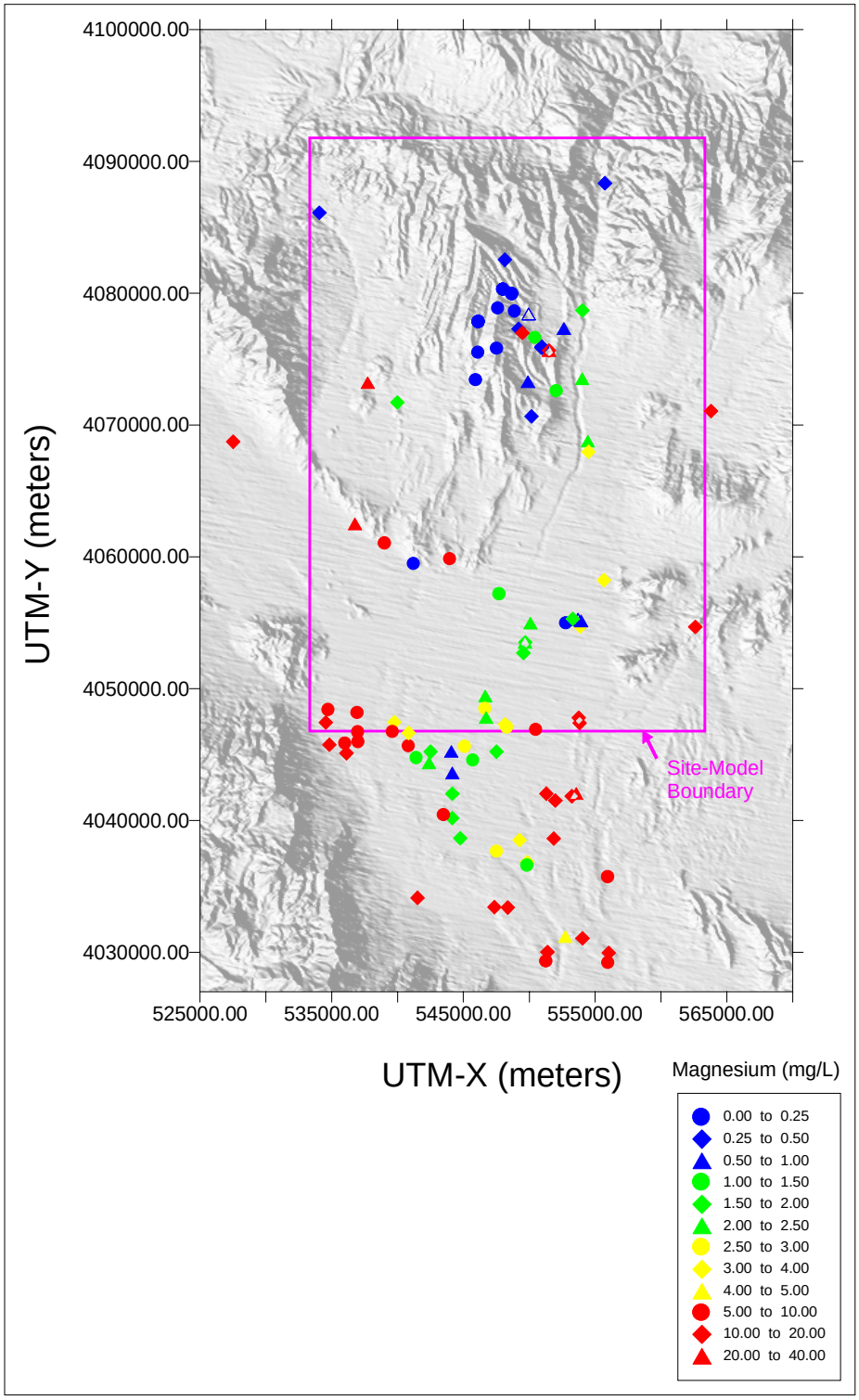
NOTE: This figure has color-coded data points and should not be read in a black and white version.

Figure 8. Areal Distribution of Calcium in Groundwater



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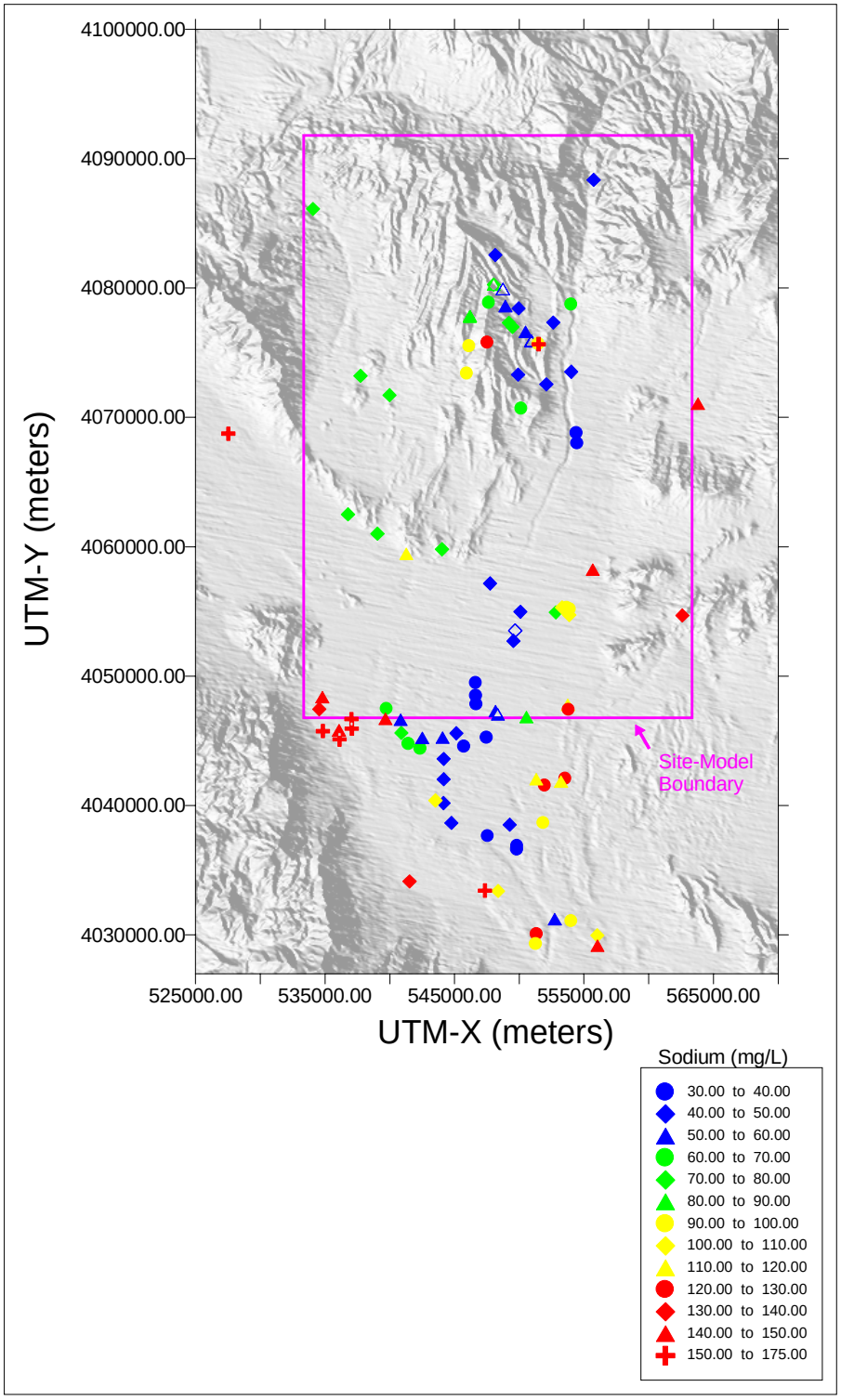
NOTE: This figure has color-coded data points and should not be read in a black and white version.

Figure 9. Areal Distribution of Magnesium in Groundwater



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NOTE: This figure has color-coded data points and should not be read in a black and white version.

Figure 10. Areal Distribution of Sodium in Groundwater

Most of the groundwater samples along Fortymile Wash have Na^+ concentrations between 35 and 50 mg L^{-1}; there are not any obvious trends in the Na^+ concentrations of groundwater beneath Fortymile Wash east of Yucca Mountain and beneath the wash in the Amargosa Desert. In the Amargosa Desert, Na^+ concentrations in groundwater increase away from Fortymile Wash in both eastward and westward directions. Groundwater in the southwest corner of the Site-Model Area has high Na^+ concentrations (130 to 180 mg L^{-1}) similar to that of the NEC Well (170 mg L^{-1}) west of Bare Mountain, whereas groundwater slightly further east along the southern boundary of the Site-Model Area has lower Na^+ concentrations similar to groundwater in Crater Flat.

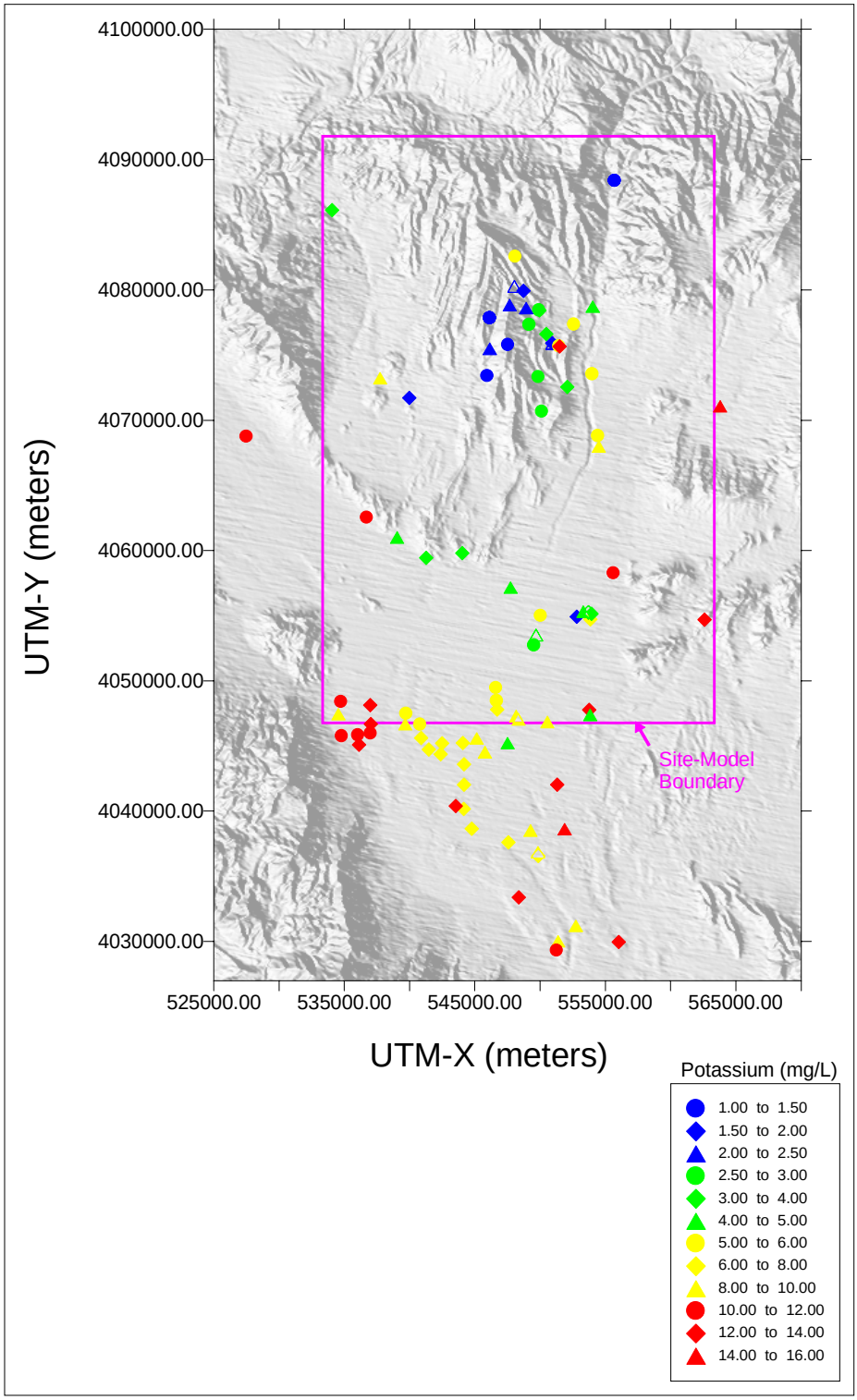
6.5.1.7 Potassium

The areal distribution of potassium (K^+) (Figure 11) shows that K^+ concentrations in groundwater at Yucca Mountain range between 1 and 6 mg L^{-1}, except in the carbonate aquifer at borehole p#1 where the K^+ concentration is 12 mg L^{-1}. The highest K^+ concentration in groundwater within the map area is at borehole J-11 in central Jackass Flats (15 mg L^{-1}). The K^+ concentrations in groundwater in western Crater Flat at borehole VH-2 is high (8 mg L^{-1}) compared to groundwater at borehole VH-1 (1.9 mg L^{-1}). In the NC-EWDP wells south of Crater Flat, K^+ concentrations range from 3.0 to 10 mg L^{-1}, with concentrations generally increasing to the west. Concentrations of K^+ are low (between 1.0 and 1.5 mg L^{-1}) at the northernmost borehole along Fortymile Wash (a#2) but are generally between 5 and 8 mg L^{-1} along the length of Fortymile Wash east of Yucca Mountain and in the Amargosa Desert. In the eastern part of the Amargosa Desert, K^+ concentrations can be both higher and lower than in groundwater near the adjacent reach of Fortymile Wash. In the southwest corner of the model area, K^+ concentrations generally are between 10 to 12 mg L^{-1}, concentrations that are similar to those of groundwater at the NEC Well west of Bare Mountain (10 mg L^{-1}).

6.5.1.8 Delta Deuterium

The areal distribution of delta deuterium (δD) values is shown in Figure 12 (this isotopic parameter is defined and discussed in Section 6.5.4.1). The δD values in groundwaters from the Yucca Mountain area range from about –104 per mil at borehole H-4 to about –99 per mil at borehole G-2. In Crater Flat, the δD values measured in water from borehole VH-1 (–108 per mil) and from Gexa Well 4 (–106 per mil) are substantially more depleted (i.e., more negative) than that for water from borehole VH-2 (–99 per mil). The δD values at borehole NC-EWDP-1D (–101.3 per mil) and at borehole NC-EWDP-3D (–105.6 per mil) are similar to the values at upgradient boreholes VH-2 and VH-1, respectively.

The δD values of groundwater near Fortymile Wash show a general trend toward more depleted values from north to south, ranging from about –93 per mil at borehole a#2 near the northern boundary of the Site-Model Area to values that are generally –100 per mil or less near the southern boundary of the model area. East of Yucca Mountain, groundwater beneath Fortymile Wash has δD values of about –97 per mil. The δD value of groundwater at borehole NC-EWDP-2D (–104 per mil) is substantially lighter than that for groundwater associated with Fortymile Wash.



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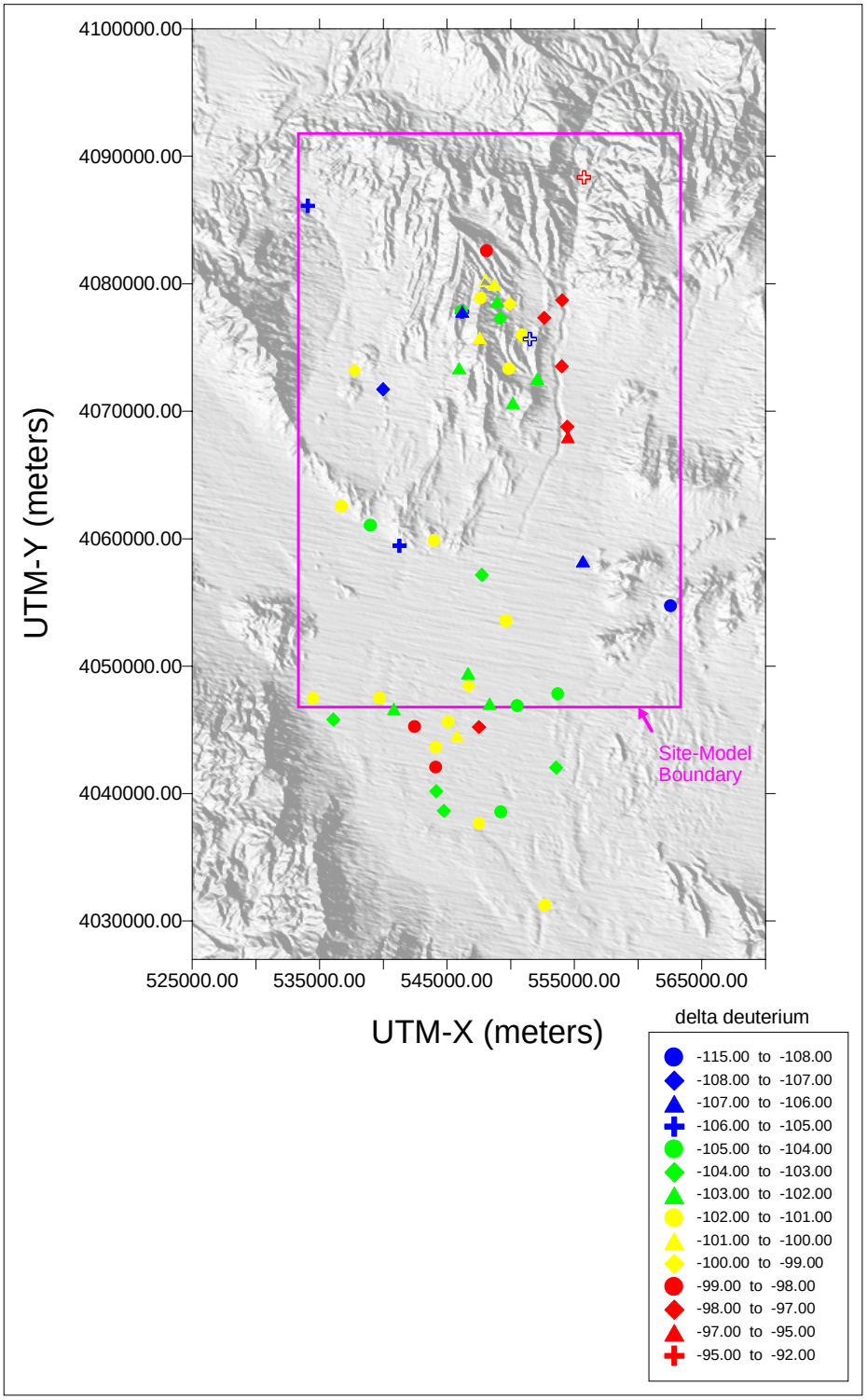
NOTE: This figure has color-coded data points and should not be read in a black and white version.

Figure 11. Areal Distribution of Potassium in Groundwater



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NOTE: This figure has color-coded data points and should not be read in a black and white version.

Figure 12. Areal Distribution of Delta Deuterium in Groundwater

Groundwater in the Amargosa Desert has variable δD values, and spatial patterns are not as regular as for other chemical species. Groundwater in the eastern part of the Amargosa Desert is generally more depleted in δD than groundwater farther to the west near Fortymile Wash. The δD values for groundwater in the southwest corner of the Site-Model Area vary between –104 and –102 per mil.

6.5.1.9 Delta Oxygen-18

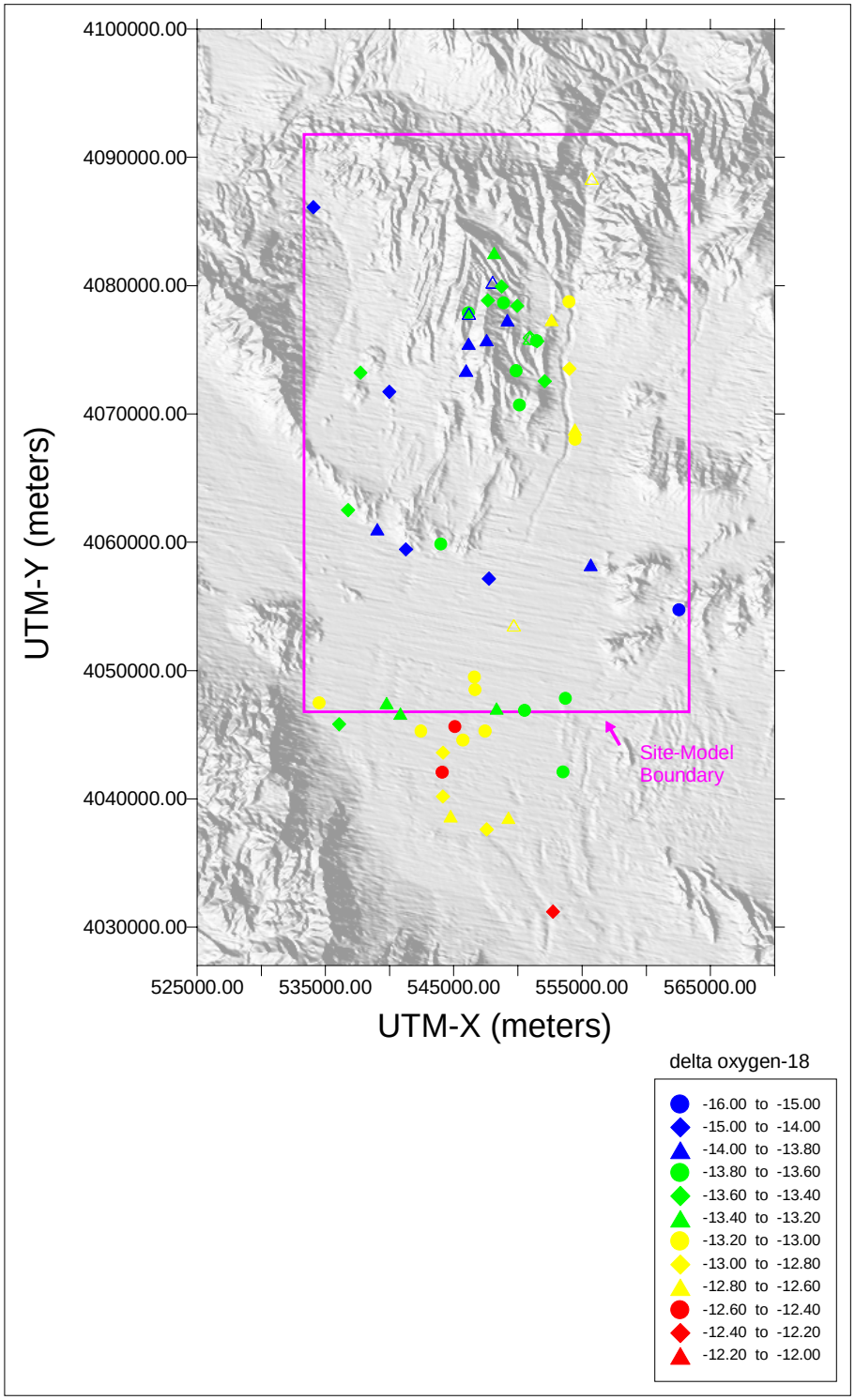
Figure 13 shows the areal distribution of delta oxygen-18 ($\delta^{18}O$) values for the Yucca Mountain area (this isotopic parameter is defined and discussed in Section 6.5.4.1). Groundwater at Yucca Mountain has $\delta^{18}O$ values between –13.3 and –14 per mil, with groundwater in western Yucca Mountain near Solitario Canyon having values that fall toward the more depleted end of this range. Groundwater at borehole VH-1 in Crater Flat has a $\delta^{18}O$ value of –14.2 per mil, similar to the $\delta^{18}O$ value for groundwater at Gexa Well 4 (–14.1 per mil), whereas groundwater at VH-2 has a $\delta^{18}O$ value of –13.4 per mil. Groundwaters sampled from the NC-EWDP wells along the southern edge of Crater Flat generally have $\delta^{18}O$ values that are similar to those in wells directly to the north at boreholes VH-1 AND VH-2.

The $\delta^{18}O$ values of groundwater near Fortymile Wash fall within a relatively narrow range (–13.2 to –12.8 per mil) north of the Amargosa Desert. The $\delta^{18}O$ values of groundwater near Fortymile Wash generally are distinct from those of groundwater farther east or west from the Wash, although near the southern boundary of the Site-Model Area, this distinction becomes less well defined.

6.5.1.10 Delta Carbon-13

The areal distribution of delta carbon-13 ($\delta^{13}C$) values is shown in Figure 14 (this isotopic parameter is defined and discussed in Section 6.5.4.1). Excluding the data from borehole p#1, where groundwater has $\delta^{13}C$ values of –2.3 per mil in the carbonate aquifer and –4.2 per mil in the volcanic aquifer, the $\delta^{13}C$ values of groundwater at Yucca Mountain vary between –14.4 per mil at borehole UZ-14 to –4.9 per mil at borehole H-3. Although patterns are complex on a borehole-by-borehole basis, groundwater in the northern part of Yucca Mountain is generally more depleted in ^{13}C than groundwater in the southern part of Yucca Mountain, which has $\delta^{13}C$ values similar to that of groundwater in Crater Flat at borehole VH-1 (–8.5 per mil). The $\delta^{13}C$ values of groundwater in the NC-EWDP boreholes at the southern edge of Crater Flat increase toward the west.

The $\delta^{13}C$ values of groundwater near Fortymile Wash generally increase between the north and south boundaries of the Site-Model Area, although local reversals in this trend are evident. The groundwater $\delta^{13}C$ values near Fortymile Wash are generally more depleted than the $\delta^{13}C$ values toward the western and eastern parts of the Amargosa Desert. The $\delta^{13}C$ values of groundwater near the southwest corner of the Site-Model Area (–5.7 and –6.2 per mil) are similar to the value at the NEC Well (–5.9 per mil) west of Bare Mountain.



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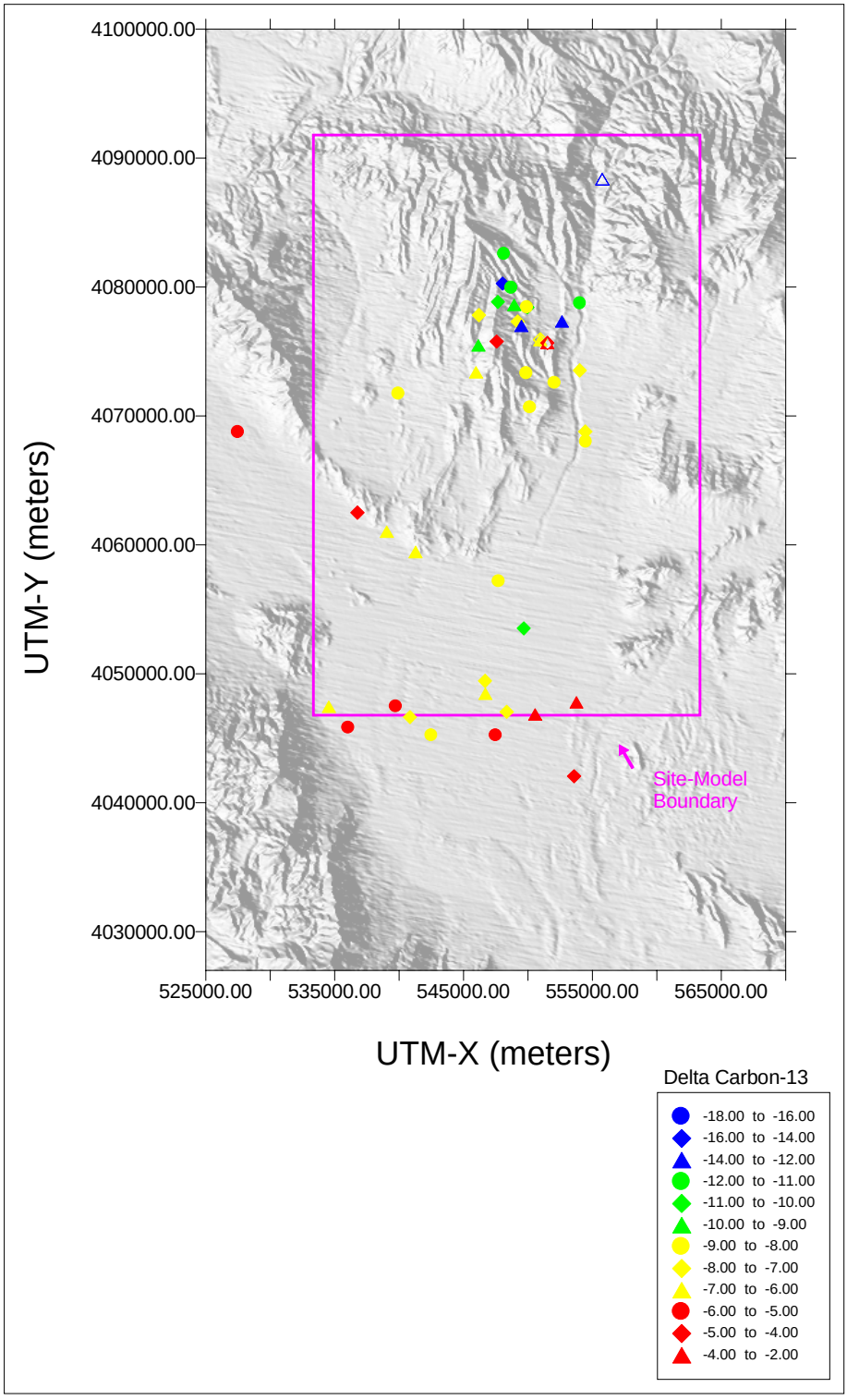
NOTE: This figure has color-coded data points and should not be read in a black and white version.

Figure 13. Areal Distribution of Delta Oxygen-18 in Groundwater



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NOTE: This figure has color-coded data points and should not be read in a black and white version.

Figure 14. Areal Distribution of Delta Carbon-13 in Groundwater

6.5.1.11 Carbon-14 Activity

The areal distribution of ^{14}C activity in pmc is shown in Figure 15. Excluding groundwater from borehole p#1, which has a ^{14}C activity of 2.3 pmc in the carbonate aquifer and 3.5 pmc in the volcanic aquifer, the ^{14}C activity of groundwater at Yucca Mountain ranges from 10.5 pmc at borehole H-3 to 25 pmc at borehole UZ-14. Groundwater at the eastern edge of Crater Flat near Solitario Canyon has some of the lowest ^{14}C activities of groundwater in the map area, with values as low as 7.3 pmc at borehole WT-10 and 10 pmc in a sample from borehole H-6. Groundwater ^{14}C activities are slightly higher farther to the west in Crater Flat at borehole VH-1 (12 pmc). The existing data indicate that groundwater at borehole NC-EWDP-3D (10 pmc) is similar to the ^{14}C activity of groundwater at borehole VH-1. The groundwater at borehole NC-EWDP-2D has a ^{14}C activity of 23.5 pmc, similar to groundwater in Dune and Fortymile Washes.

Groundwater near Fortymile Wash has ^{14}C activities that range from over 60 pmc at borehole a#2 near the northern boundary of the model area to values under 20 pmc near the southern boundary of the model area. South of the southern boundary of the Site-Model Area, ^{14}C activities range from 10 to 40 pmc. The single groundwater ^{14}C activity measured in the southwest corner of the Site-Model Area is 31 pmc, which is considerably larger than the value of 12 pmc measured in Crater Flat and similar to the value of 29 pmc measured in groundwater at the NEC Well west of Bare Mountain.

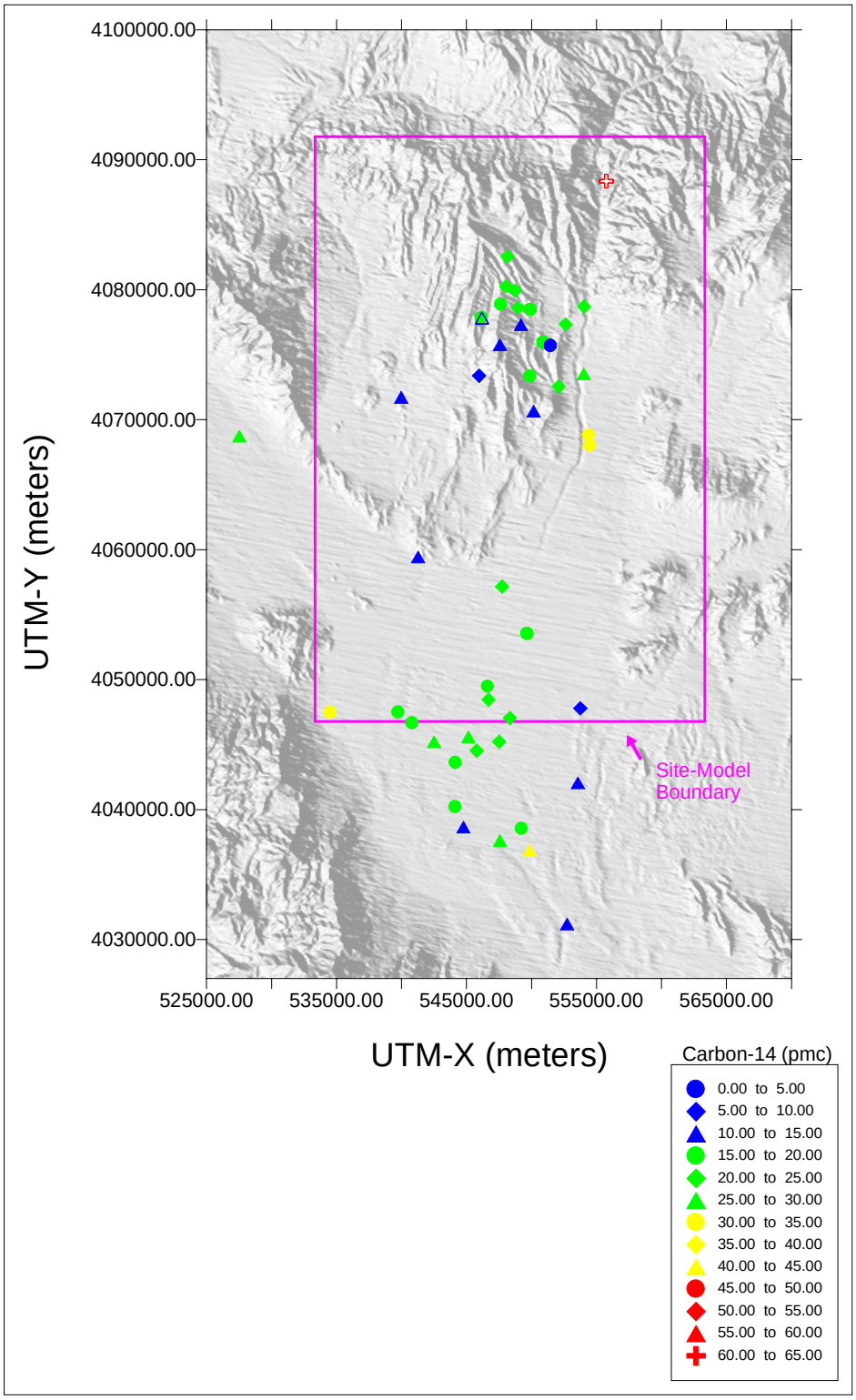
6.5.1.12 $^{234}U/^{238}U$ Activity Ratios

Figure 16 shows the areal distribution of uranium concentrations and $^{234}U/^{238}U$ activity ratios. The highest activity ratios in the region are found at Yucca Mountain and are localized in an area between the Yucca Mountain crest and the eastern edge of Busted Butte and between the northern extent of Yucca Mountain and just south of Busted Butte. The activity ratios decrease in all directions from this central area. Moving southward along the Fortymile Wash drainage, the ratios first increase to values from 4.5 to 6.0 at wells J-13 and J-12 then decrease to values below 3.0 in the northern Amargosa Desert. In Crater Flat, the ratios decrease from east to west.

6.5.2 Regional Flow Paths Inferred from Hydrochemical Data

Groundwater flow paths were estimated from areal plots of dissolved ions and isotopes based on compositional differences and similarities between areas. The potentiometric surface map (Figure 4) was used to determine which areas of similar chemical and isotopic composition could potentially be located along the same flow path with allowances made for the possibility that flow paths could be somewhat oblique to the potentiometric gradient because of possible anisotropy in permeability.

Groundwater chemistry can vary for a number of reasons, including changes in the composition of recharge waters over time, variable soil/rock/water/gas interactions, and mixing between waters of different compositions. This preliminary analysis assumes that the groundwater chemistry data obtained on a water sample from a given well is representative of the groundwater at that location (Assumption 2 in Table 4). That is, it is assumed vertical variations in groundwater chemistry in the volcanic aquifer at a given location are insignificant (Assumption 4). Given this assumption, the available water chemistry data can be used to define flow paths in two dimensions and to interpret relations between groundwaters from different regions (Assumption 4).



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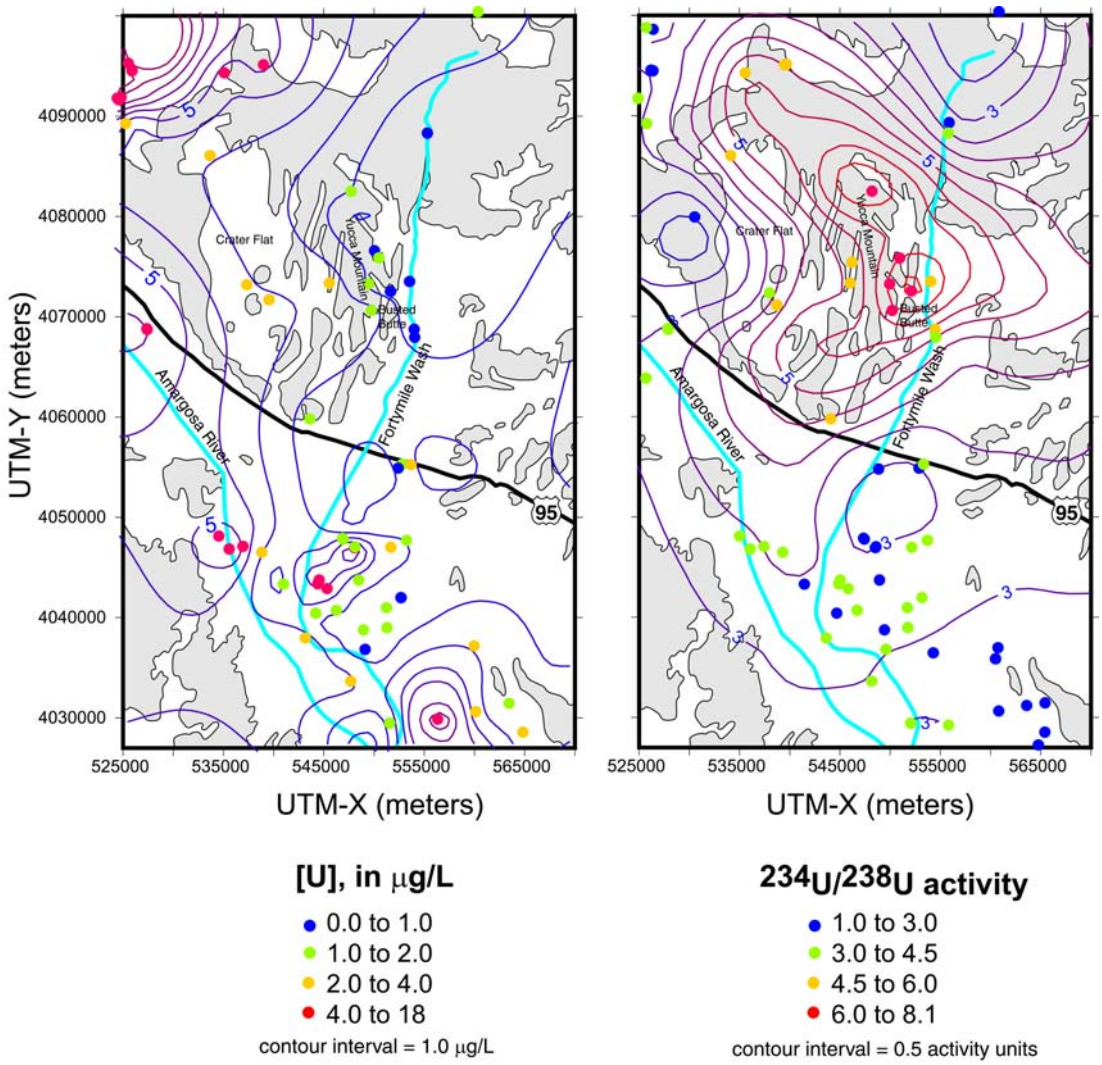
NOTE: This figure has color-coded data points and should not be read in a black and white version.

Figure 15. Areal Distribution of Carbon-14 in Groundwater



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NOTE: This figure has color-coded data points and should not be read in a black and white version.

Figure 16. Areal Distributions of Uranium Concentration and $^{234}U/^{238}U$ Activity Ratio in Groundwater

In general, the various chemical constituents in groundwater are affected to widely varying extents by soil/rock/water/gas interactions. Some readily measured constituents such as chloride, bromide, and the isotopes of hydrogen and oxygen show minimal effects from soil/rock/water/gas interactions at ambient aquifer temperatures. The concentrations of these constituents are controlled primarily by the composition of recharge waters and by mixing of waters of different compositions. That is, these constituents show conservative behavior (Langmuir 1997, p. 292). Because the isotopic compositions of hydrogen and oxygen in recharge waters have almost certainly changed over time, it is to be expected that isotopic variability would be evident in groundwaters of different ages (Benson and Klieforth 1989, Fig. 11; Winograd et al. 1992, Fig. 2).

Flow paths can be traced using conservative constitutents only where compositional differences exist that allow some directions to be eliminated as possible flow directions. Some chemical and isotopic species in some areas have relatively uniform compositions and, thus, provide no information about flow paths. In other areas, they show more distinct compositional differences and, thus, can be used to infer flow directions. Because no single chemical or isotopic species varies sufficiently to determine flow paths everywhere in the study area, multiple chemical and isotopic species are used to construct the flow paths inferred in this section.

The analysis of flow paths that follows assumes that Cl^- and SO_4^{2-} values are conservative in addition to certain chemical species, such as δD, $\delta^{18}O$, Na^+, and Ca^{2+} (Assumption 5 in Table 4). None of these species is truly conservative. For example, there are potential mineral sources of SO_4^{2-} in the map area. Additionally, groundwater in the carbonate aquifer is high in both Cl^- and SO_4^{2-} compared to groundwater in the volcanic aquifer (Figures 5 and 6), so upwelling from the carbonate aquifer could potentially modify the concentrations of Cl^- and SO_4^{2-} in the volcanic aquifer. In spite of the potential nonconservatism of Na^+ and Ca^{2+}, the contrast in concentrations between some areas is great enough that meaningful inferences about flow directions can be made.

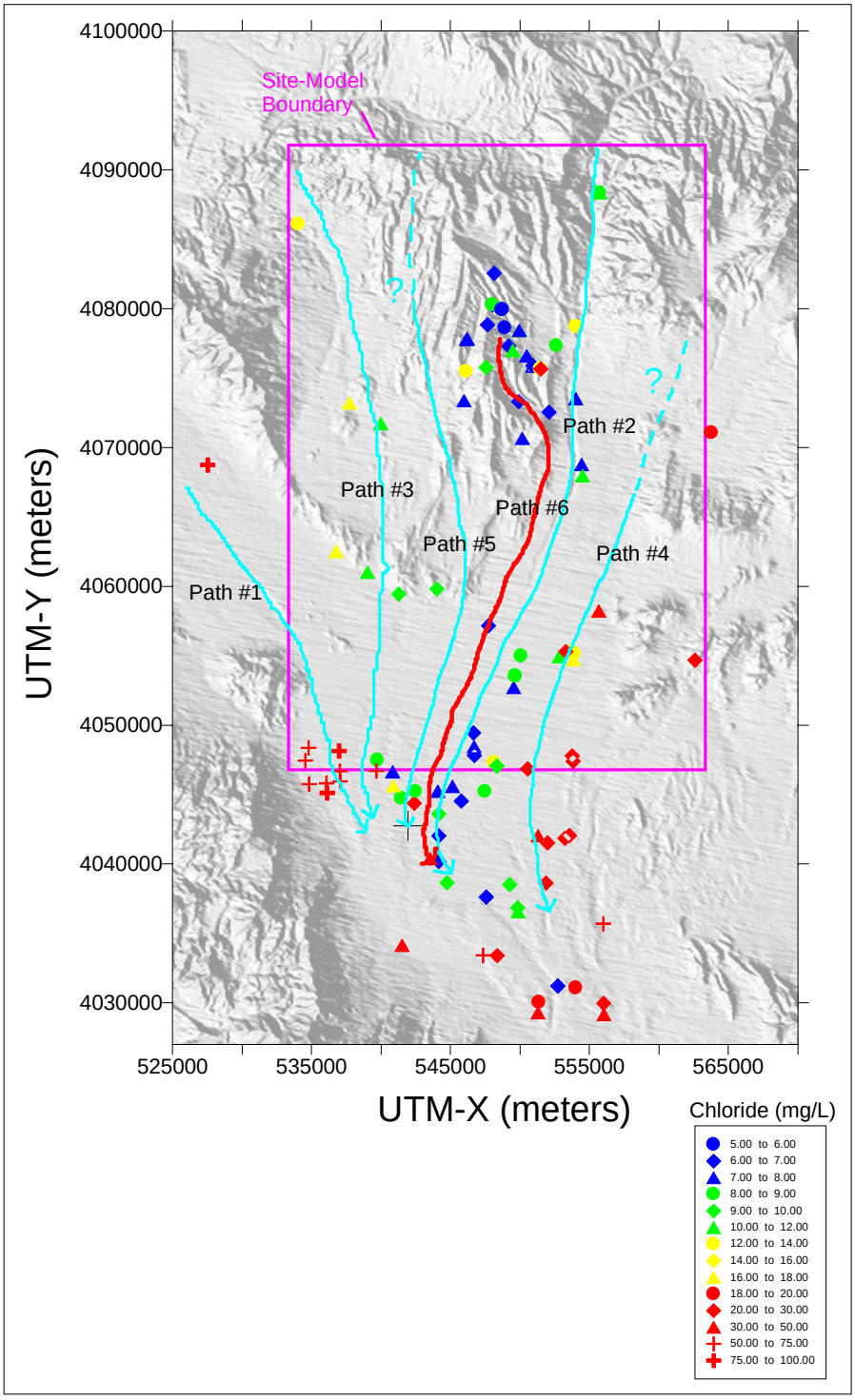
6.5.2.1 Regional Flow Paths

The flow paths determined from the areal distribution maps described in Section 6.5.1 are superimposed on a map showing the areal distribution of chloride (Figure 17). These paths were developed, in part, based on the maps of other chemical and isotopic data. The reasoning by which each of the flow paths were developed follows.

Flow Path 1 connects the area in the vicinity of the NEC Well west of Bare Mountain with the area in the southwest corner of the model area. A more north-south flow path from Crater Flat to the southwest corner of the map area was ruled highly improbable based on the dissimilarities in Cl^- and Na^+ values in these two areas (Figures 5 and 10).

Flow Path 2 connects areas near Fortymile Canyon and Fortymile Wash northeast and east of Yucca Mountain with the Fortymile Wash area in the Amargosa Desert. This flow line is constrained on the east by the much higher Cl^-, SO_4^{2-}, and Na^+ concentrations in groundwater in Jackass Flats and the southeast corner of the model area (Figures 5, 6, and 10). Near Yucca Mountain, the position of this flow line is constrained on the west by the distinct δD and $\delta^{18}O$ composition of groundwater at Yucca Mountain (Figures 12 and 13), including groundwater at the CIND-R-LITE and NC-EWDP-2D wells south of Yucca Mountain. Near the southern boundary of the Site Model, Flow Path 2 is constrained by the higher Cl^-, SO_4^{2-}, and Na^+ concentrations of groundwater west of the Wash (Figures 5, 6, and 10).

Flow Path 3 connects areas in the northwest corner of the Site-Model Area, central Crater Flat, the NC-EWDP wells, and wells along the southern boundary of the Site Model. The flow path is constrained on the west by the higher Cl^-, SO_4^{2-}, and Ca^{2+} concentrations in western Crater Flat at borehole VH-2, the western NC-EWDP wells at the southern edge of Crater Flat, and the southwestern corner of the Site-Model boundary (Figures 5, 6, and 8). Additional constraints are



DTN: GS000700012847.001, GS930108315213.002, GS950808312322.001, MO0007MAJIONPH.002, MO0007MAJIONPH.003, MO0007MAJIONPH.005, MO0007MAJIONPH.006, MO0007MAJIONPH.007, MO0007MAJIONPH.008, MO0007MAJIONPH.009, MO0007MAJIONPH.010, MO0007MAJIONPH.011, MO0007MAJIONPH.012, MO0007MAJIONPH.013, MO0007MAJIONPH.014, MO0007MAJIONPH.015, MO0008MAJIONPH.017

NOTE: This figure has color-coded data points and should not be read in a black and white version. Flow paths are drawn based on Assumptions 4 and 5 in Table 4.

Figure 17. Regional Flow Paths Inferred from Hydrochemical and Isotopic Data

imposed by the distinct δD and $\delta^{18}O$ composition of groundwater at boreholes VH-1 and VH-2 in central Crater Flat (Figures 12 and 13) and by the distinctly higher Na^+ concentration of groundwater in the southwest corner of the model area (Figure 10). The starting location for this flow path was determined based on the similarity of the SO_4^{2-} and Ca^{2+} concentrations and δD and $\delta^{18}O$ values of groundwater at Gexa Well 4 in the northwest corner of the model area to groundwater at VH-1 in central Crater Flat (Figures 6, 8, 12, and 13). The Cl^- and Na^+ concentrations of groundwater at Gexa Well 4 were not clearly associated with groundwater in either western or eastern Crater Flat (Figures 5 and 10).

Flow Path 4 connects areas in central Jackass Flats and Amargosa Valley to wells located south of the model boundary near the Gravity Fault. This flow path was defined by the western extent of groundwater with high Cl^-, SO_4^{2-}, and Na^+ concentrations east of Fortymile Wash (Figures 5, 6, and 10). The position of this flow path is poorly constrained by data in central Jackass Flats and may be further to the west than is shown, as also indicated by the fact that the high Ca^{2+} and SO_4^{2-} concentrations at borehole J-11 have no downgradient counterparts. Near the southeast corner of the Site-Model Area, groundwaters east of the flow path are isotopically lighter than groundwaters west of the flow path, supporting the contention that groundwaters east and west of this flow path have different origins (Figures 12 and 13). No isotopic data are available from borehole J-11 to provide possible links between groundwaters in central Jackass Flats and downgradient groundwaters. The bicarbonate concentrations in the southeast corner of the model are also much higher than that for groundwater from borehole J-11 (Figure 7), indicating possible interaction of groundwater from Jackass Flats with carbonate rocks that crop out in the area or another source of water altogether contributing to the southeast corner of the model area.

The location of Flow Path 5 was based primarily on contrasts between the relatively high Cl^- and SO_4^{2-} concentrations of groundwater in Crater Flat and the much lower Cl^- and SO_4^{2-} concentrations of groundwater under Yucca Mountain and Fortymile Wash (Figures 5 and 6). The distal end of the flow line was a point near the southern boundary of the flow model that had Cl^- and SO_4^{2-} concentrations intermediate between the groundwater typical of Yucca Mountain and Crater Flat. This line was then extended upgradient through southern Yucca Mountain and Crater Flat. Because of the lack of data toward the upper part of the flow-model area, the flow path in this area is queried.

The regional flow paths constructed on the basis of the hydrochemical and isotopic data (Figure 17) are generally consistent with flow paths that could be inferred from the potentiometric surface (Figure 4), but they have a stronger north-south component. This stronger north-south component could be reflecting the general north-south structural fabric of the rock, the inability of the method to account for vertical heterogeneities in groundwater chemistry within a borehole, or simply the sparseness of data in certain regions of the model area. It is interesting that regional flow lines appear to be traceable from hydrochemical and isotopic data even where flow lines converge to the discharge areas south of the model boundary, suggesting long-term stability of the hypothesized flow paths over thousands to tens of thousands of years.

6.5.2.2 Likely Flow Paths from the Potential Repository Area

General flow paths in the Yucca Mountain area were constructed by identifying areas that had similar concentrations of conservative chemical species, such as chloride or sulfate, and tracing a path through these chemically similar areas in a downgradient direction. Of particular interest for this report are the paths leading from the potential repository area, such as the one constructed primarily on the basis of groundwater chloride concentrations (Figure 17). This pathway (Flow Path 6) starts with groundwater from the repository area just east of Yucca Mountain Crest that has chloride concentrations of about 6 mg L^{-1}. The pathway follows wells along Dune Wash with similarly low chloride concentrations before turning south-southwest near Fortymile Wash. Well WT#12, located immediately south of Dune Wash, has a chloride concentration of 7.8 mg L^{-1}, indicating that the dilute water beneath Dune Wash probably flows southeast along the Dune Wash Fault towards Fortymile Wash before turning south-southwest, rather than flowing directly south under Dune Wash. From the intersection of Dune Wash and Fortymile Wash, the only downgradient borehole with a chloride concentration of approximately 6 mg L^{-1} is borehole NC-EWDP-2D. Groundwater at this borehole has a $\delta^{18}O$ value of –14.1 per mil, a value that indicates this water was probably not derived from the Fortymile Wash where $\delta^{18}O$ values are generally –13.2 to –12.8 per mil (Figure 13). Borehole NC-EWDP-2D provides the basis for extending Flow Path 6 south-southwest from the Dune Wash/Fortymile Wash area along the western margin of Fortymile Wash. South of borehole NC-EWDP-2D, the pathway is constrained by the presence of two areas of groundwater with much higher chloride concentrations: (1) a western zone, composed of groundwater flowing south from Crater Flat and, possibly, southeast from Oasis Valley; and (2) an eastern zone, composed of groundwater flowing southwest from Jackass Flats and from leakage upward from the carbonate aquifer near the Gravity Fault (Winograd and Thordarson 1975, pp. C84–C85, C112). Groundwater in wells south of NC-EWDP-2D with chloride concentrations of approximately 6 mg L^{-1} have isotopic (δD and $\delta^{18}O$) characteristics that indicate the water may have been recharged by overland flow during the late Pleistocene (Section 6.5.7.2.1). The hypothesized flow path was extended south from NC-EWDP-2D by keeping the path to the west of the axis of Fortymile Wash and east of the more highly concentrated water from Crater Flat and Oasis Valley.

Importantly, the chloride data shown in Figure 17, as well as other chemical and isotopic data, suggest that groundwater from beneath the potential repository area does not flow along the south-trending faults in the southern part of the mountain. This conclusion is consistent with the potentiometric surface map that indicates that groundwater in this area probably flows from Crater Flat.

6.5.3 Evaluation of Evidence for Local Recharge

In this subsection, uranium-isotope ratio data ($^{234}U/^{238}U$ activity ratios) are presented that indicate that local recharge is present in the saturated-zone waters beneath Yucca Mountain. This conclusion is further evaluated using data on the concentrations of major anions and cations.

6.5.3.1 Description of Perched-Water Data

Perched water was encountered in at least five boreholes at Yucca Mountain: USW UZ-14, USW NRG-7a, USW SD-9, USW SD-7, and USW WT-24. The perched-water samples were obtained by bailing or by pumping, depending on factors related to the drilling of the borehole. In general, it is believed that pumping produces a water sample more likely to represent in-situ chemical and isotopic conditions. Drilling has the potential to affect the chemical and isotopic composition of water in the borehole by putting foreign drilling fluids (generally air) into contact with the water in the borehole and, also, by grinding the rock and thereby exposing fresh, unaltered rock surfaces that may react with the water. If a water sample is bailed without first pumping the borehole to remove the water contacted by the drilling fluids and ground rock, the representativeness of the water sample of in-situ conditions is uncertain. By first purging the borehole of water present in the borehole at the time of drilling and drawing many borehole volumes of additional water from the formation into the borehole before sampling, confidence is gained that the water sample represents actual chemical conditions in the formation.

Of the perched-water samples considered in this analysis, samples from boreholes SD-9 and NRG-7a (Table 7) were obtained exclusively by bailing (Yang and Peterman 1999, Table 19) during a hiatus in drilling following the encounter with the perched water. No pumping was done prior to sample collection at these boreholes.

Perched-water samples from UZ-14 (Table 7) obtained prior to August 17, 1993, were obtained without first pumping the borehole. Pumped samples were obtained between August 17 and August 27, 1993, and an additional bailed sample was taken after pumping on August 31. A time series of delta strontium-87 ($\delta^{87}Sr$) versus water production showed that $\delta^{87}Sr$ values continued to evolve until about 12,000 liters had been pumped from the borehole, or sometime after August 25 (Yang and Peterman 1999, Table 19, Fig. 113). Therefore, the $\delta^{87}Sr$ data, and perhaps other data, obtained from UZ-14 after this date probably best represent in-situ conditions.

Perched water from borehole SD-7 sampled on March 8, 1995, was obtained by bailing prior to pumping. Perched-water samples obtained from borehole SD-7 between March 16 and March 21, 1995, were obtained by pumping (Yang et al. 1996, p. 37).

Perched water was sampled by pumping from borehole WT-24. However, according to Patterson et al. (1998, p. 277), the isotopic data obtained prior to the end of the 24-hour pumping test conducted on October 21 to 22, 1997, were collected during what the authors considered to be a clean-out period.

In summary, the perched-water data are thought to represent in-situ conditions to varying degrees, depending on whether the samples were bailed or pumped and the extent to which the borehole was cleaned out prior to sampling. The data collected from borehole SD-7 on or after March 16, 1995, from borehole UZ-14 after August 25, 1993, and from borehole WT-24 on October 22, 1997, are thought to best represent the actual chemical and isotopic conditions of the perched water at Yucca Mountain. These samples are weighted more heavily than the remaining samples in developing the conclusions of this report.

6.5.3.2 Evidence from $^{234}U/^{238}U$ Activity Ratios

As a consequence of radioactive decay, ^{234}U is preferentially enriched relative to ^{238}U in migrating groundwater (Osmond and Cowart 1992, Fig. 9.1). The primary causes for this enrichment are the greater solubility of ^{234}U due to radiation damage of crystal lattice sites containing ^{234}U atoms (Szilard-Chalmers effect) and the greater probability that these ^{234}U atoms have been converted to the more soluble uranyl ion due to the effects of radiation-induced ionization (Gascoyne 1992, section 2.5.1). In addition, decay of ^{238}U can cause the displacement of the intermediate ^{234}Th daughter (which rapidly decays to ^{234}U) off of crystal surfaces into the adjacent water by alpha-recoil processes. The amount of excess ^{234}U relative to ^{238}U is controlled by ^{234}U decay, water/rock ratios, flow-path length, uranium concentrations in the host rock, and the rate of rock dissolution in the aquifer. For this study, ^{234}U decay is insignificant.

Meteoric water (that is, precipitation) interacts with readily soluble soil components resulting in soil waters that contain relatively large amounts of both ^{234}U and ^{238}U derived by bulk dissolution (DTN: GS960908315215.013 and GS980908312322.009). Measured $^{234}U/^{238}U$ activity ratios in secondary minerals formed in soil zones on Yucca Mountain range from 1.4 to 1.8 (DTN: GS960908315215.013 and GS980908312322.009).

Pore waters extracted from core samples from the unsaturated zone at Yucca Mountain have $^{234}U/^{238}U$ activity ratios that range from 1.5 to 3.0. Pore waters extracted from the top of the Paintbrush Tuff nonwelded hydrogeologic unit (PTn) have $^{234}U/^{238}U$ activity ratios of 1.5 to 2.5, whereas pore waters from the upper lithophysal unit of the welded Topopah Spring Tuff (Tpt) have $^{234}U/^{238}U$ activity ratios of 2.5 to 3.8 (DTN: GS991299995215.001, data set MOL.20000104.0007). These data suggest there is a general increase in $^{234}U/^{238}U$ activity ratios in pore waters from the soil zone down through the upper unsaturated zone.

Analyses of $^{234}U/^{238}U$ activity ratios in perched-water samples range from 3.5 at borehole SD-7 to 8.4 at borehole WT-24 (DTN: GS960908315215.013 and GS980108312322.003). The values at the high end of this range are unusual and suggest the existence of certain flow conditions. In particular, the high ratios are consistent with small intermittent fluxes of water passing through a fracture network. As a result of processes associated with alpha recoil during the decay of ^{238}U, the ^{234}U daughter product tends to be more readily mobilized than the parent ^{238}U. In fractures that are not continuously or frequently flushed, these processes allow ^{234}U to preferentially accumulate over time relative to ^{238}U. When a small flux of water flows through such a fracture, it may preferentially incorporate ^{234}U relative to ^{238}U, resulting in water with an elevated $^{234}U/^{238}U$ ratio. The accumulation of such small water fluxes could result in perched water with the observed high $^{234}U/^{238}U$ ratios. The changes to the $^{234}U/^{238}U$ activity ratios that would occur over time within the perched water are uncertain. Changes, if any, in the $^{234}U/^{238}U$ activity ratio of the perched water would depend on the ^{238}U content of the host rock, the water volume to fracture-surface area (a function of fracture density and aperture), redox conditions, and other factors (Clark and Fritz 1997, pp. 238–240). The $^{234}U/^{238}U$ activity ratio of the perched water might either increase or decrease with time, depending on the relative importance of these factors.

Table 7. Chemical and Isotopic Composition of Perched Water at Yucca Mountain

Water sample	Depth (m)	Sampling Method	Date	Chemical Concentrations (mg L^{-1})									^{13}C (‰)	^{14}C (pmc)	^{3}H[a,c] (TU)	δD (‰)	$\delta^{18}O$ (‰)	$^{234}U/^{238}U$ Activity ratio	$^{36}Cl/Cl$ (x 10^{-15})
				pH	Ca	Mg	Na	K	Cl	SO_4	HCO_3	SiO_2							
SD-7	479.76	Bailed	03-08-95	—	14.2	0.13	45.5	5.3	4.4	9.1	112	62.3	–10.4	34.4	6.2	–99.8	–13.4	—	511
	488.29	Pumped	03-16-95	8.1	13.3	0.13	45.5	5.3	4.1	9.1	128	57.4	–9.4	28.6	—	–99.7	–13.3	—	—
	488.29	Pumped	03-17-95	8.2	12.8	0.08	45.8	5.5	4.1	8.6	130	50.9	–9.5	28.4	—	–99.6	–13.4	3.504	657
	488.29	Pumped	03-20-95	8.0	12.9	0.07	45.5	5.4	4.1	8.5	127	55	–9.5	27.9	—	–99.6	–13.4	3.58	—
	488.29	Pumped	03-21-95	8.2	13.5	0.08	44.6	5.5	4.1	10.3	128	55.9	–9.5	28.4	< 0.3	–99.6	–13.3	3.69	609, 635
SD-9	—	Bailed	03-07-94	—	—	—	—	—	—	—	—	—	–14.4	41.8	0	–97.8	–13.3	—	—
	—	Bailed	07-07-94	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2.42[b]	—
	453.85	Bailed	07-17-94	8.6	2.9	0.2	98	9.8	5.6	27.6	197[d]	64.2	–14.4	41.8	0	–97.8	–13.3	—	449
	—	Bailed	09-12-94	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2.42[b]	—
UZ-14 A	384.60	Bailed	08-02-93	7.6	23	1.8	39	5.6	7.9	14.3	150	34.2	–10.2	41.7	0.3	–98.6	–13.8	—	559
UZ-14 A2	384.60	Bailed	08-02-93	7.8	24	1.8	38	3.9	9.1	13.8	148.8	36.4	–10.1	40.6	3.1	–97.5	–13.5	—	538
UZ-14 B	387.68	Bailed	08-03-93	8.1	31	2.7	40	4.4	8.3	16.3	147.6	51.4	–9.5	36.6	0	–97.1	–13.4	—	566
UZ-14 C	390.75	Bailed	08-05-93	8.3	45	4.1	88	5.8	15.5	223	106.1	7.7	–9.2	66.8	0.4	–87.4	–12.1	—	389
UZ-14 PT-1	390.75	Pumped	08-17-93	—	37	3.1	40	6.3	7.2	57.3	144	21.4	–9.8	32.3	1.8	–97.8	–13.3	—	644
UZ-14 PT-2	390.75	Pumped	08-19-93	—	30	2.4	35	3.3	7.0	22.9	144	25.7	—	28.9	3.1	–97.9	–13.4	—	656
UZ-14 PT-4	390.75	Pumped	08-27-93	—	27	2.1	34	1.8	6.7	14.1	141.5	32.1	–9.6	27.2	0	–97.3	–13.4	7.56	675
UZ-14 D	390.75	Bailed	08-31-93	7.8	31	2.5	35	4.1	7.0	24.2	146.4	40.7	–11.3	29.2	0	–97.6	–13.1	—	690

Table 7 (Continued). Chemical and Isotopic Composition of Perched Water at Yucca Mountain

Water sample	Depth (m)	Sampling Method	Date	Chemical Concentrations (mg L^{-1})									^{13}C (‰)	^{14}C (pmc)	^{3}H[a,c] (TU)	δD (‰)	$\delta^{18}O$ (‰)	$^{234}U/^{238}U$ Activity ratio	$^{36}Cl/Cl$ (x 10^{-15})
				pH	Ca	Mg	Na	K	Cl	SO_4	HCO_3	SiO_2							
WT-24[e]	—	Pumped	10-06-97	—	—	—	—	—	—	—	—	—	—	—	—	–99.6	–13.4	4.36[b]	—
		Pumped	10-16-97	—	—	—	—	—	—	—	—	—	—	—	—	—	—	6.58[b]	—
		Pumped	10-17-97	—	—	—	—	—	—	—	—	—	—	—	—	—	—	8.33	—
		Pumped	10-22-97	8.1	23	1.4	37	2.4	9.0	16	135	46	–11.8	29.6	<0.3	–99.4	–13.5	8.34	586
NRG-7a	—	Bailed	03-04-94	—	—	—	—	—	—	—	—	—	—	—	—	—	—	5.17[b]	518
	460.25	Bailed	03-07-94	8.7	3	0	42	6.8	7	4	114	9	–16.6	66.9	10	–93.9	–12.8	—	474
	—	Bailed	03-08-94	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

DTN: GS980108312322.005 (ions, $\delta^{13}C$, δD, $\delta^{18}O$, ^{3}H), GS950808312322.001 (^{3}H), GS980108312322.003 ($^{234}U/^{238}U$ activity ratios), GS991299992271.001 (^{3}H), LAJF831222AQ98.011 ($^{36}Cl/Cl$), MO0007GNDWTRIS.003 (^{14}C), MO0007GNDWTRIS.013 ($\delta^{13}C$, δD, $\delta^{18}O$, ^{14}C), MO0007MAJIONPH.016 (chemistry)

NOTES: "—" not available

[a]Tritium analyses have an accuracy of plus or minus 12 TU.

[b]These results are not representative of in-situ conditions due to sample contamination

[c]These data are included for reference only.

[d]This sample also contains 10 mg L^{-1} CO_3

[e]Average values of samples collected on October 22, 1997

As shown in Figure 18, saturated-zone waters also tend to have relatively high $^{234}U/^{238}U$ activity ratios compared to soil waters and unsaturated-zone pore waters at Yucca Mountain. Interestingly, waters from the shallow saturated zone beneath Yucca Mountain tend to have higher ratios than saturated-zone waters from adjacent areas (for example, Crater Flat, Fortymile Wash, and Highway 95; Figure 16). High $^{234}U/^{238}U$ activity ratios in saturated-zone waters from the area between the crest of Yucca Mountain and the eastern boundary of Busted Butte strongly suggest these waters contain a large perched-water component (Assumption 6 in Table 4). An attempt to quantify this proportion is presented in Section 6.5.6.

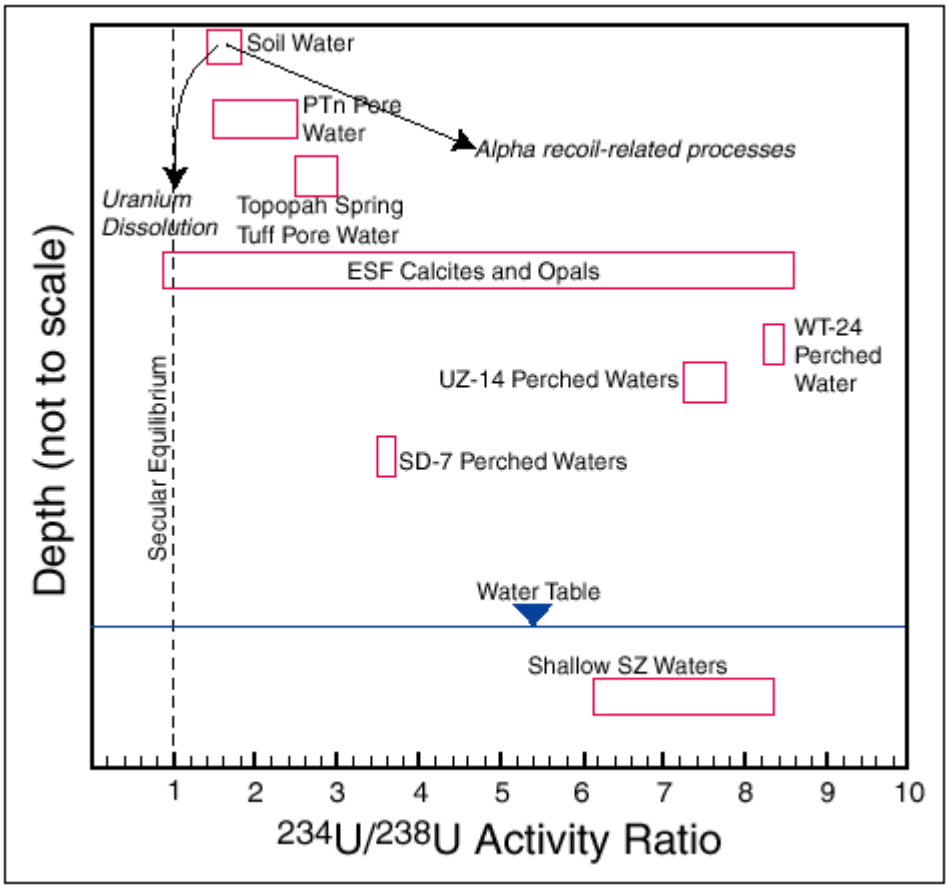


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Figure 18. Comparison of $^{234}U/^{238}U$ Activity Ratios in Saturated-Zone Waters to Ratios in Soil Waters and Unsaturated-Zone Pore Waters at Yucca Mountain

6.5.3.3 Evidence from Other Chemical Constituents

The concentrations measured for the major cations and anions in saturated-zone waters in the Yucca Mountain vicinity have proportions very similar to those found in perched waters, as shown in the trilinear diagram in Figure 19. The main differences in the major cation compositions of these waters involve calcium and magnesium. Perched waters have somewhat higher concentrations of these constituents than most saturated-zone waters at Yucca Mountain. This result could reflect the fact that saturated-zone waters have a high probability of coming in contact with zeolite minerals, which are known to have a high affinity for calcium and magnesium. In all, the major ion data for perched and saturated-zone waters are also consistent with the idea that the saturated-zone waters beneath Yucca Mountain contain a high proportion of perched water.

6.5.4 Evaluation of Evidence for Timing of Recharge

Hydrochemical data that potentially bear on the question of the age or timing of local recharge include hydrogen and oxygen isotope ratios and ^{14}C radioactivities. Hydrogen and oxygen isotope ratios potentially contain age information because the numerical values of these ratios in groundwaters reflect the climate under which the waters were infiltrated. Therefore, if waters were recharged in a climatic regime different from the current regime, this fact should be reflected in the isotope ratios of the groundwaters.

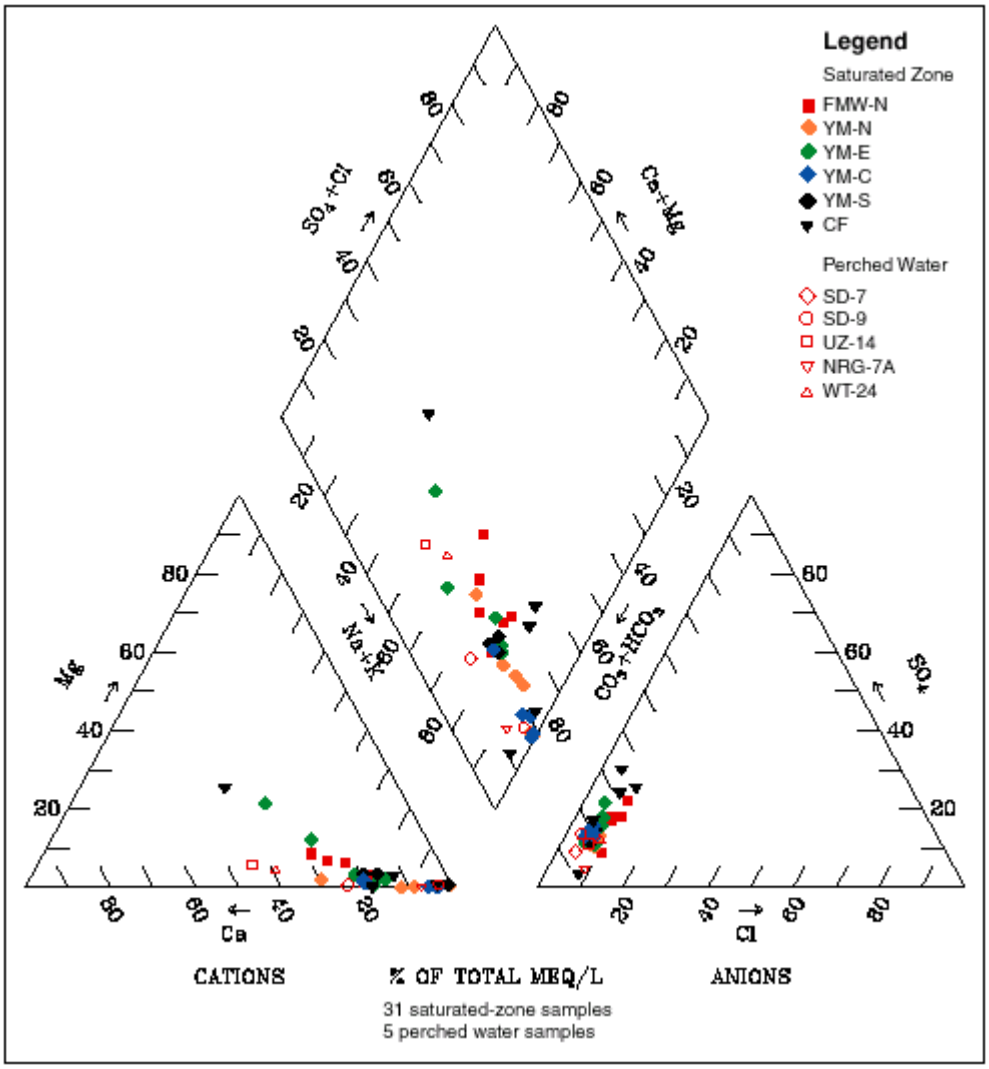
The activity of ^{14}C in a particular groundwater sample potentially offers a more direct indication of the time at which that groundwater was recharged. In general, the older the sample, the lower the ^{14}C activity. However, the interpretation of the age of a groundwater sample from ^{14}C activity data is complicated by the fact that groundwaters can undergo soil/water/rock/gas interactions that can alter the proportions of carbon isotopes in a groundwater sample. This process, in turn, can lead to modification of the age calculated for the sample based on ^{14}C activity as discussed further below.

6.5.4.1 Evidence from Hydrogen and Oxygen Isotope Ratios

Hydrogen and oxygen isotope ratios are useful for tracing groundwater movement where spatial differences in their concentrations exist that allow different parts of the groundwater system to be distinguished. Both hydrogen and oxygen are composed of more than one stable isotope. The stable hydrogen isotopes of interest here are ^{1}H and ^{2}H. The latter isotope is commonly referred to as deuterium with the chemical symbol D. The ratio of these two isotopes is measured and is generally reported in δ notation as follows, with units of per mil:

$$\delta D = [(D/^{1}H)_{sample}/(D/^{1}H)_{standard} - 1] \times 1000 \qquad \text{(Eq. 1)}$$

The standard used for these measurements is known as Vienna Standard Mean Ocean Water (VSMOW) (Clark and Fritz 1997, p. 8).



DTN: GS930108315213.002, GS950808312322.001, MO0007MAJIONPH.003, MO0007MAJIONPH.004, MO0007MAJIONPH.005, MO0007MAJIONPH.006, MO0007MAJIONPH.007, MO0007MAJIONPH.011, MO0007MAJIONPH.012, MO0007MAJIONPH.013, MO0007MAJIONPH.014, MO0008MAJIONPH.017

NOTE: Open symbols are perched waters; closed symbols are groundwaters.

Figure 19. Trilinear Diagram Comparing Compositions of Perched Waters and Saturated-Zone Groundwaters

The stable oxygen isotopes of interest here are ^{16}O and ^{18}O. The ratio of these isotopes is measured and also reported in δ notation as follows, with units of per mil:

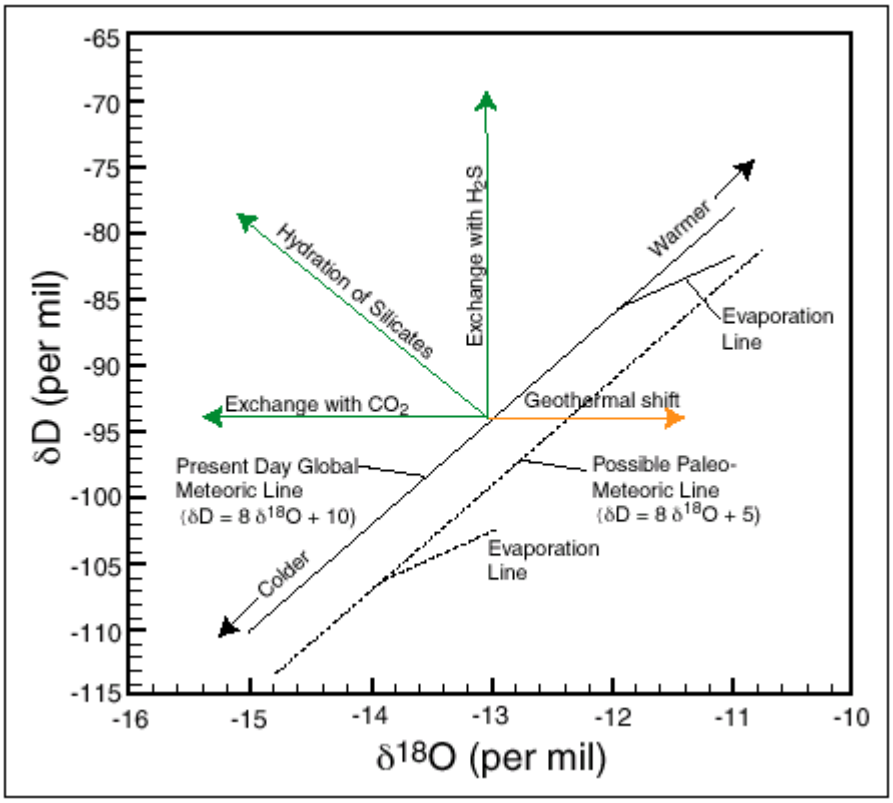
$$\delta^{18}O = [(^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{standard} - 1] \times 1000 \quad \text{(Eq. 2)}$$

Vienna Standard Mean Ocean Water (VSMOW) is also used as the standard for oxygen isotope measurements (Clark and Fritz 1997, p. 8).

The ^{2}H and ^{18}O atoms are part of the water molecule and, at low temperatures, are generally less affected by water/rock interactions than most major cations and anions. The values of δD and $\delta^{18}O$ in precipitation, fresh surface water, and groundwater are typically negative because of fractionation between the heavy and light isotopes of hydrogen and oxygen during evaporation over the initial moisture source area and because the residual water vapor becomes progressively more depleted in the heavier isotopes (^{2}H and ^{18}O) during successive precipitation events. A detailed discussion of all the processes affecting the isotopic composition of precipitation and recharge, and possible effects of water-rock interactions, is beyond the scope of this report. A summary of these processes is available in textbooks, such as Clark and Fritz (1997, Chps. 2–4, 9). Some of the net effects of these processes are depicted in Figure 20.

The values of δD and $\delta^{18}O$ in precipitation are strongly correlated on a global basis. This correlation has been termed the "global meteoric water line." The equation for this line is $\delta D = 8\ \delta^{18}O + 10$ (Clark and Fritz 1997, p. 36). The slope of the line is related to the ratio of the equilibrium fractionation factors for ^{2}H and ^{18}O, which is approximately 8.2 at 25ºC (Clark and Fritz 1997, p. 50). Locally, the isotopic composition of precipitation may follow a line with a somewhat different slope and intercept. Such lines have been referred to as the "local meteoric water line." The deuterium "excess" is the intercept in the meteoric water line when the slope is 8. This "excess" has been shown to be inversely related to the relative humidity of the air in the moisture source area (Clark and Fritz 1997, p. 45; Merlivat and Jouzel 1979, p. 5029).

One of the primary factors affecting the isotopic composition of precipitation is condensation temperature, which is a function of season, elevation, and climate. Precipitation falling during periods when temperatures are low has more negative ("depleted") δD and $\delta^{18}O$ values than precipitation falling during warm periods. Because average surface temperatures are correlated with elevation, precipitation falling at higher elevations tends to have more negative isotope ratios than precipitation falling at lower elevations. Late Pleistocene groundwater, identified by carbon-14 age dating or other techniques, is often more isotopically depleted compared to modern waters because it was recharged under conditions that were cooler than at present. Also, because of the inverse relation between the value for the deuterium excess and relative humidity of the moisture source areas, data for old groundwaters recharged during pluvial periods in the Pleistocene sometimes plot below the present-day global or local meteoric water line (Clark and Fritz 1997, pp. 198–199, Fig. 8-2).



DTN: N/A-reference only; Source: based on Clark and Fritz (1997, Figures 2-1, 2-9, 2-11, and 9-1)

Figure 20. Effects of Different Processes on Delta Deuterium and Delta Oxygen-18 Composition of Subsurface Water

Despite seasonal variations in the δD and $\delta^{18}O$ composition of precipitation, the isotopic composition of the recharge water in humid regions is generally close to the average volume-weighted isotopic composition of precipitation. In arid climates, the isotopic composition of the recharge can be substantially different from the average volume-weighted isotopic composition of precipitation because of the preferential recharge of winter precipitation (see, for example, Ingraham et al. 1991, p. 256) and because of evaporation prior to recharge. Generally, evaporation shifts the δD and $\delta^{18}O$ composition of the infiltrating water to the right of the meteoric water line. The slope of the evaporation line increases with increasing relative humidity of the air (Clark and Fritz 1997, Fig. 2-8). The slope of the evaporation line ranges between 3.9 and 4.5 for relative humidities between 0 and 50 percent, which encompasses the range of relative humidities typical of Yucca Mountain during the summer months.

Once in the ground, interaction between groundwater and the solid surfaces in soil or rock can cause the $\delta^{18}O$ composition of groundwater to be shifted horizontally to the right of the meteoric water line. This interaction is facilitated by high temperatures such as those associated with known geothermal fields (Clark and Fritz 1997, pp. 250–255). At low temperatures, these interactions are kinetically inhibited. However, under special circumstances, interactions between groundwater and silicate minerals, or between groundwater and subsurface gases, may cause the isotopic compositions of groundwater to be shifted to the left of the meteoric water line (Clark and Fritz 1997, Fig. 9-1). The special circumstances typically involve alteration of rock to clays at high rock/water ratios or, in the case of gases, proximity to gas vents associated with volcanoes. Note that hydrogen isotope ratios are not generally affected as much by water/rock

interactions as oxygen isotope ratios because rocks generally contain much less hydrogen than water on a volume-to-volume basis.

Many of the effects of seasonal and long-term temperature changes described in the preceding paragraphs have been reported for the Yucca Mountain area. Seasonal variations in the isotopic values of precipitation were reported by Ingraham et al. (1991, p. 248, Fig. 3) and by Benson and Klieforth (1989, Table 1a) for a number of sites at different elevations in the NTS vicinity. The average monthly volume-weighted $\delta^{18}O$ values of precipitation were shown by Ingraham et al. (1991, Figs. 3 and 4) to vary between about –14 per mil in March and April and –3 per mil in August. The $\delta^{18}O$ of springs discharging from perched water was generally shifted from the average volume-weighted $\delta^{18}O$ of precipitation toward the values typical of winter precipitation (Ingraham et al. 1991, Figs. 10 and 11), supportive of the concept that winter precipitation is preferentially recharged in arid regions.

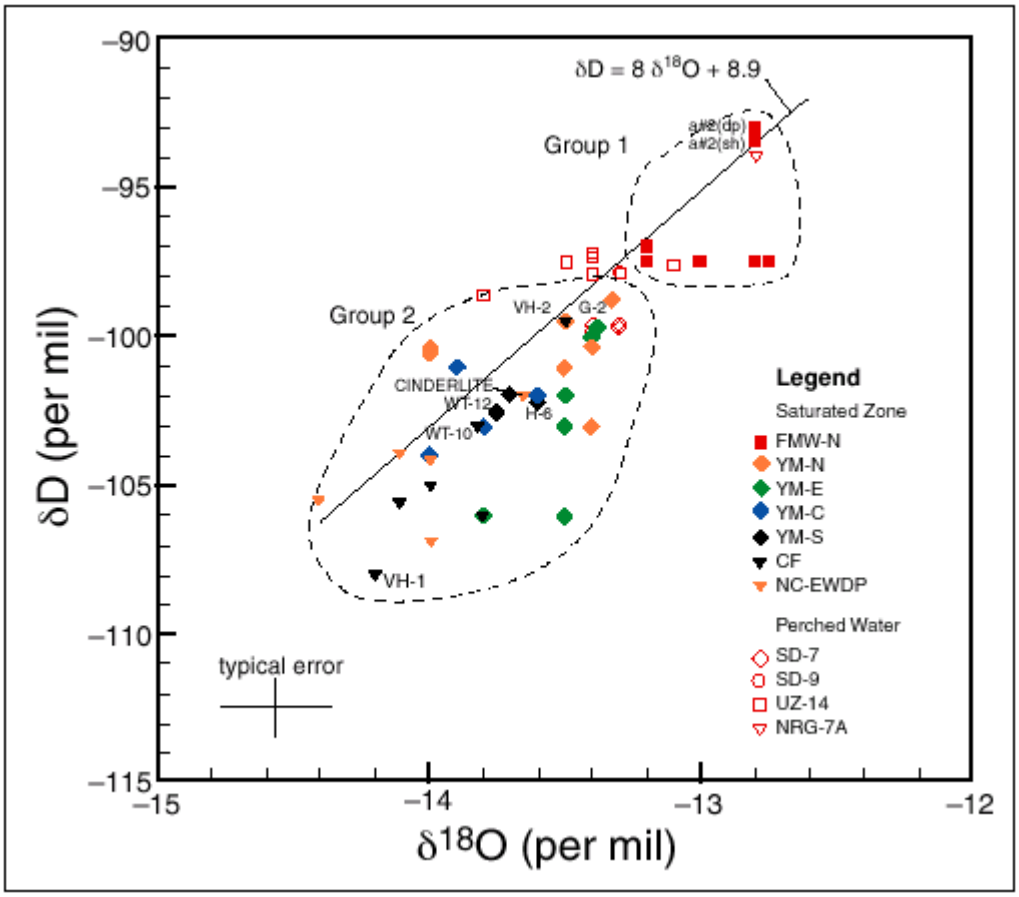
The effects of temperature differences associated with climate change may be evident in the data reported for Yucca Mountain groundwaters. Benson and Klieforth (1989, Fig. 11) noted a correlation between $\delta^{18}O$ values and the ^{14}C age of groundwaters near Yucca Mountain. Waters are more depleted in ^{18}O with increasing age between 9,000 and 18,500 yr ago, a trend they attributed to the colder temperatures existing at the time the older water was recharged. Variations in the $\delta^{18}O$ compositions of groundwater discharging in the Ash Meadows area at Devil's Hole 55 km southeast of Yucca Mountain were preserved in calcites deposited between 570,000 and 60,000 yr before the present (Winograd et al. 1992, Figs. 2 and 3). These variations were shown to correlate well with known glacial and interglacial episodes during the period of record, with $\delta^{18}O$ decreasing, on average, by 1.9 per mil during glacial periods.

The δD and $\delta^{18}O$ values of regional groundwater samples and perched-water samples at Yucca Mountain are plotted in Figure 21. Also plotted in this figure is a local meteoric water line ($\delta D = 8\ \delta^{18}O + 8.9$) as defined by Benson and Klieforth (1989, Fig. 14) from snow samples obtained from Yucca Mountain. Snow samples were used to define the local meteoric water line because these samples were less likely to be affected by evaporation than rain samples, especially samples of light summer rains that can have a substantial fraction of their volume evaporated before reaching the ground.

The local groundwater data have been separated into two groups in terms of δD and $\delta^{18}O$ values. The first group is defined by samples from the northern Fortymile Wash area and includes samples from boreholes a#2, WT#15, JF#3, J-13, and J-12. Based on its chemical and isotopic characteristics, groundwater from borehole WT#14 seems to be associated with this group, despite its location approximately 1.8 km west of the Wash. This well will be included with the Fortymile Wash group of boreholes (Group 1) in subsequent discussions. Perched water samples have isotopic values similar to those of the low-δD saturated-zone samples in Group 1 (FMW-N). The second group (Group 2) includes all the other saturated-zone water samples from the Yucca Mountain area.

Group 1 samples have relatively heavy δD and $\delta^{18}O$ values compared to groundwater from other boreholes at Yucca Mountain and have relatively consistent δD values (excluding the a#2 sample). The scatter in the data points within Group 1 probably reflects a combination of analytical errors and evaporation. The a#2 sample was obtained from upper Fortymile Canyon at a site of active recharge (Savard 1994, p. 1805). The relative enrichment of the δD and $\delta^{18}O$

values at borehole a#2 likely reflects the fact that this water is young and was recharged under current climatic conditions. The remainder of samples in Group 1 appear to have been infiltrated under slightly cooler climatic conditions than those reflected in the a#2 sample. However, the fact that these samples have heavier δD and $\delta^{18}O$ values compared to groundwaters in Group 2 suggests Group 1 waters were infiltrated under warmer conditions than the prevailing conditions for Group 2 samples.



DTN: GS000700012847.001, GS950808312322.001, GS970708312323.001, MO0007GNDWTRIS.002, MO0007GNDWTRIS.003, MO0007GNDWTRIS.005, MO0007GNDWTRIS.006, MO0007GNDWTRIS.007, MO0007GNDWTRIS.008, MO0007GNDWTRIS.009, MO0007GNDWTRIS.010, MO0007GNDWTRIS.012, MO0007GNDWTRIS.013, USGS (n.d.) (see assumption 23 in Table 4), (data are listed in Tables 3 and 7)

NOTE: This figure has color-coded data points and should not be read in a black and white version. The solid line is the local meteoric water line from Benson and Klieforth (1989, Fig. 14).

Figure 21. Delta Deuterium and Delta Oxygen-18 Data for Perched Water and Groundwater Near Yucca Mountain

The samples in Group 2 come from wells west of Fortymile Wash on Yucca Mountain and in Crater Flat. The range in $\delta^{18}O$ for all the samples from the Yucca Mountain area is about 2 per mil, which is about the range in $\delta^{18}O$ expected between interglacial and glacial periods from the Devil's Hole data (Winograd et al. 1992, Fig. 2). Therefore, the lightest (i.e., most negative) δD and $\delta^{18}O$ values shown in Figure 21 for samples from Group 2 are consistent with the hypothesis that the groundwaters they represent were infiltrated primarily during the late Pleistocene or early Holocene. Whether the range in δD and $\delta^{18}O$ values within Group 2 samples reflects infiltration under a range of climatic regimes or mixing of older and younger groundwaters cannot be resolved on the basis of δD and $\delta^{18}O$ values alone.

6.5.4.2 Evidence from Carbon Isotope Data

6.5.4.2.1 Carbon-14 Ages of Saturated-Zone Groundwaters

Theoretically, the activity of ^{14}C in a groundwater sample reflects the time at which the water was recharged. Unfortunately, precipitation waters are generally very dilute and have a high affinity for dissolution of solid phases in the soil zone, unsaturated zone, and/or saturated zone. In particular, in the transition from precipitation compositions to groundwater compositions, the bicarbonate + carbonate concentration in the water commonly increases by several orders of magnitude (Langmuir 1997, p. 292, Table 8.7). Because bicarbonate is the principal ^{14}C-containing species in most groundwaters, the source of this additional bicarbonate can have a major impact on the "age" calculated from the ^{14}C activity of a given water sample. If the source is primarily decaying plant material in an active soil zone, the calculated "age" for the water sample should be close to the real age. On the other hand, if the source of the bicarbonate is dissolution of old (10^4 yr) calcite with low ^{14}C activity, the calculated age for the sample will be too old.

A useful measure of the source of the carbon in a water sample is the $\delta^{13}C$ value of the sample because this value is different for organic materials compared to calcites. The $\delta^{13}C$ value is defined as follows, and expressed in units of per mil:

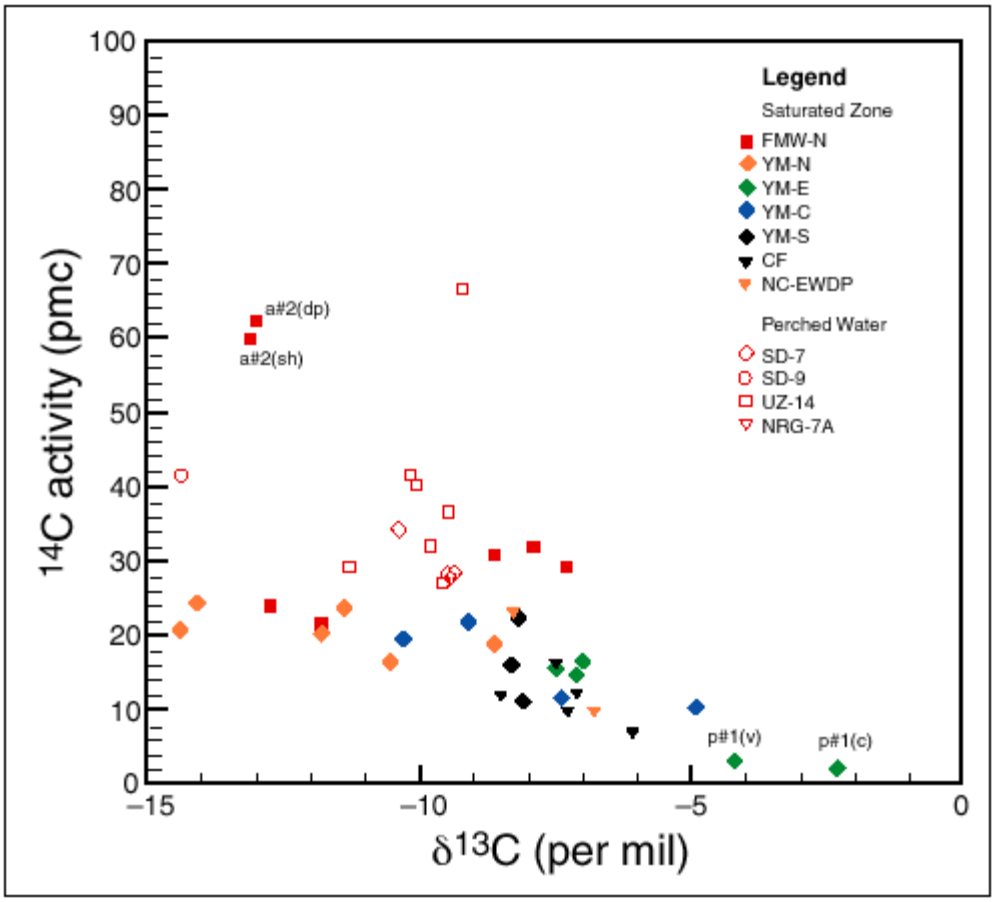
$$\delta^{13}C = [(^{13}C/^{12}C)_{sample}/(^{13}C/^{12}C)_{standard} - 1] \times 1000 \qquad \text{(Eq. 3)}$$

The standard used for reporting stable carbon isotope measurements is carbon from a belemnite fossil from the Cretaceous Peedee formation in South Carolina (Clark and Fritz 1997, p. 9).

The $\delta^{13}C$ values of carbon species typical of the soil waters in arid environments range from –25 to –13 per mil (Forester et al. 1999, p. 36). At Yucca Mountain, pedogenic carbonate minerals have $\delta^{13}C$ values that generally are between –8 and –4 per mil, although early-formed calcites are also present that have $\delta^{13}C$ values greater than 0 per mil (Forester et al. 1999, Fig. 16; Whelan et al. 1998, Fig. 5). Paleozoic carbonate rocks typically have $\delta^{13}C$ values close to 0 per mil (Forester et al. 1999, Fig. 16; Whelan et al. 1998, Fig. 5).

Values for $\delta^{13}C$ and ^{14}C (in percent modern carbon, pmc) in perched waters and groundwaters from the Yucca Mountain area are plotted in Figure 22. Excluding the perched-water and the Fortymile Wash area (FMW-N) samples, the $\delta^{13}C$ and ^{14}C values reported for the groundwater samples appear to be negatively correlated. In the absence of chemical reactions and/or mixing, waters moving from source areas to Yucca Mountain should experience no change in $\delta^{13}C$ but

their ^{14}C activity should decrease with time. If waters infiltrating into the source area had more or less constant $\delta^{13}C$ values, data points for waters infiltrated at different times would form a vertical trend in Figure 22. The fact that the data points in the figure do not form a vertical trend suggests either that the $\delta^{13}C$ of waters infiltrated at the source areas are not constant or that chemical reactions or mixing have affected the carbon isotope values. If waters that infiltrate into the source areas have randomly variable $\delta^{13}C$ ratios, then a random relation between $\delta^{13}C$ and ^{14}C values would be expected. Rather the $\delta^{13}C$ and ^{14}C values for Yucca Mountain and Crater Flat groundwaters are well correlated as shown in Figure 22.



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NOTE: This figure has color-coded data points and should not be read in a black and white version.

Figure 22. Carbon-14 Activity Versus Delta Carbon-13 of Perched Water and Groundwater Near Yucca Mountain

It has been noted that $\delta^{13}C$ values in infiltrating waters reflect the types of vegetation present at the infiltration point. According to the data of Quade and Cerling (1990, p. 1550), the $\delta^{13}C$ of modern water infiltrated in cooler climates (for example, at higher elevations) is more negative than for modern water infiltrated in warmer climates (for example, at lower elevations). This relation would result in a positive correlation in Figure 22 because the older samples (that is,

lowest pmc) plotted would tend to have the most negative $\delta^{13}C$ (that is, they infiltrated when the climate was cooler than it is now). Because the observed correlation in the groundwater values is negative instead of positive, the primary cause of the correlation must involve some other process(es).

A likely cause of the negative correlation evident in Figure 22 is the dissolution of carbonate minerals such as calcite. For example, calcite with a $\delta^{13}C$ value of –4 per mil and a ^{14}C activity of zero could readily explain the correlation if it were being dissolved by infiltrating soil waters. This explanation assumes that points on the regression line are of the same age but that the water dissolved different amounts of calcite. In this explanation, the scatter of points about the regression line could represent samples of slightly different ages. For example, δD and $\delta^{18}O$ data suggest that groundwaters from the northern part of Fortymile Wash (FMW-N) and the perched waters have younger ages than most Yucca Mountain groundwaters. This observation is consistent with the data plotted in Figure 22.

The data points for water samples from drillhole a#2 are of particular interest because they represent recent infiltration (see below). As shown in the figure, the ^{14}C activities in these two samples are only 60 and 62 pmc. This result suggests these samples obtained a significant fraction of their bicarbonate concentrations from a source with little or no ^{14}C activity. Interestingly, these samples have lower $\delta^{13}C$ values than most groundwaters from the Yucca Mountain area. This result suggests the bicarbonate source was not calcite typical of the soil zone on Yucca Mountain as these have $\delta^{13}C$ values between –2 and –8 per mil (Whelan et al. 1998, Fig. 5).

To attempt to quantify the impact of calcite dissolution on "ages" calculated for groundwaters from Yucca Mountain, mass-balance calculations using the code NETPATH (Plummer et al. 1994, pp. 24–30) were carried out. For each groundwater sample, the initial water available to react with the rock and soil gas was assumed to be pure water that had equilibrated with atmospheric concentrations of CO_2 ($10^{-3.5}$ atm) (Assumption 16 in Table 4); therefore, the NETPATH models considered the net chemical changes in a water sample from the time it condensed as precipitation up until the time of sampling. The assumed values for the ^{14}C activities (^{14}A) of atmospheric CO_2 (100 pmc) and of calcite and dolomite (0 pmc) (Assumption 14) were combined with estimates of the amount of carbon contributed to the water sample by these phases to estimate the initial ^{14}C activity of the samples prior to decay ($^{14}A_0$). The values of $^{14}A_0$ were then used with the measured ^{14}A of the water sample in the radioactive decay equation to determine the corrected ^{14}C age of the groundwater. NETPATH returned two possible models for each groundwater sample, with and without the dissolution of pyrite and the formation of zeolite as a reaction product:

Pure water + X_1 calcite + X_2 Ca^{2+}/Na^{+} exchange + X_3 $CO_2(g)$ + X_4 NaCl + X_5 gypsum + X_6 dolomite + X_7 glass + X_8 SiO_2 = groundwater + X_9 zeolite + X_{10} clay (Model 1)

Pure water + X_1 calcite + X_2 Ca^{2+}/Na^{+} exchange + X_3 $CO_2(g)$ + X_4 NaCl + X_5 gypsum + X_6 dolomite + X_7 glass + X_8 SiO_2 + X_9 pyrite = groundwater + X_{10} clay. (Model 2)

Each X_i represents the number of millimoles per liter of phase i dissolving into or precipitating out of solution or, in the case of Ca^{2+}/Na^{+} exchange, sorbing or desorbing from the mineral surface. Because the models estimated that the amounts of pyrite dissolved and the amounts of zeolite and clay precipitated were small, the two models resulted in nearly identical corrected ^{14}C

ages. For brevity, only the results from the second model are given in Table 8. Dolomite, although not an important mineral phase in rocks above the carbonate aquifer, was assumed to be available to interact with the water as aeolian dust deposited at the land surface from dolomite outcrops located upwind of Yucca Mountain (Assumption 15 in Table 4). Although limited sampling has not confirmed the presence of Mg-bearing carbonates, such as dolomite, in dust at Yucca Mountain, the assumption of wind-blown dolomite dust as a source for Mg^{2+} is not expected to substantially affect the calculations because of the generally very low concentrations of Mg^{2+} in the groundwater. Gypsum and NaCl were assumed to have been available at the land surface as dust or as minerals precipitated from soil-zone water concentrated by evapotranspiration. Other minerals included in the model are known to be present in the tuffs at Yucca Mountain (Bish and Chipera 1989, Appendix A).

The estimated values of $^{14}A_0$ used to calculate the corrected ages are generally about 50 pmc (Table 8) because the reaction models estimated that approximately 50% of the carbon was derived from atmospheric CO_2 with an assumed ^{14}C activity of 100 pmc and 50% of the carbon was derived from either calcite or dolomite with an assumed ^{14}C activity of 0 pmc (Assumption 14). The ^{14}C activity of calcite in the deep unsaturated zone and in the saturated zone is probably close to 0 pmc based on the distribution of ^{14}C ages of calcite from the deep unsaturated zone (Whelan et al. 1998, Fig. 9). If shallow calcite dissolved by infiltrating water had a ^{14}C activity similar to that of CO_2 dissolved in the water, then no substantial dilution of the ^{14}C activity of the water would result from calcite dissolution. The true values of $^{14}A_0$ and the ^{14}C ages of the groundwater samples may have been underestimated by the values in Table 8 because the NETPATH models assumed that all calcite had a ^{14}C activity of 0 pmc; however, at least some of the calcite in the water samples probably originated from the soil zone where ^{14}C activities are significantly nonzero. On the other hand, the effects of this assumption are partially counterbalanced by the assumption that all of the CO_2 entered into solution in the soil zone where the ^{14}C activity of the gas is probably near 100 pmc. If CO_2 is dissolved deep in the unsaturated zone where the ^{14}C activity of CO_2 may be much less than 100 pmc (Yang et al. 1996, Fig. 20), the corrected ^{14}C ages would be erroneously old.

The values of $^{14}A_0$ from known recharge areas indicate that corrections to groundwater ^{14}C ages are necessary but that the values of $^{14}A_0$ may be slightly higher than indicated by Table 8 (average $^{14}A_0 = 50 \pm 6$ for 34 samples). Thomas et al. (1996, p. C51) reported that water samples from recharge areas in the central Spring Mountains and Sheep Range, west and north of Las Vegas, respectively, had bomb-pulse concentrations of tritium but were saturated with calcite and had ^{14}C activities of 76 to 100 pmc. The presence of bomb-pulse tritium indicates that the ^{14}C activity of the water should also have contained a component of young water with ^{14}C activities greater than 100 pmc because of elevated ^{14}C activity in the atmosphere following atmospheric nuclear testing. Dilution of the ^{14}C of recharge water by the dissolution of calcite is also indicated by data from samples from borehole a#2 in Fortymile Canyon, which had ^{14}C activities of 60 and 62 pmc and tritium concentrations of 37 pCi L^{-1} (12 TU) (DTN: MO0007GNDWTRIS.010). Water levels in boreholes adjacent to borehole a#2 have shown a rapid

Table 8. Results of NETPATH Corrections to Groundwater ^{14}C Ages

Sample	$m_{calcite}$	$m_{Ca/Na}$	m_{CO2}	m_{NaCl}	m_{gypsum}	$m_{dolomite}$	m_{glass}[a]	m_{pyrite}	m_{SiO2}	m_{clay}[b]	$\delta^{13}C$	^{14}A	$^{14}A_0$	Uncorrected ^{14}C age[c] (yr)	Corrected ^{14}C age[c] (yr)
J-12	0.664	0.672	1.240	0.206	0.209	0.167	0.335	0.010	0.041	0.159	–7.9	32.2	55.9	9,368	4,565
J-13	0.799	0.763	1.205	0.200	0.157	0.125	0.329	0.010	0.108	0.156	–7.3	29.2	54.0	10,176	5,085
b#1(bh)	1.016	0.845	1.255	0.240	0.215	0.051	0.230	0.007	0.277	0.109	–10.55	16.7	53.4	14,795	9,607
b#1(Tcb)	1.067	0.867	1.302	0.211	0.208	0.051	0.184	0.006	0.461	0.087	–8.6	18.9	53.2	13,772	8,551
c#1	1.115	1.094	1.367	0.209	0.232	0.029	0.131	0.004	0.596	0.062	–7.1	15.0	54.3	15,683	10,633
c#2	1.107	1.053	1.138	0.200	0.221	0.033	0.138	0.004	0.546	0.066	–7.0	16.6	49.8	14,845	9,085
c#3	1.105	1.076	1.110	0.203	0.223	0.031	0.125	0.004	0.563	0.059	–7.5	15.7	49.3	15,306	9,465
p#1(v)	1.878	1.762	4.377	0.367	0.374	0.454	0.368	0.011	–0.126	0.175	–4.2	3.5	61.2	27,713	23,659
p#1(c)	1.973	2.749	10.612	0.791	1.620	1.698	0.789	0.024	–1.337	0.375	–2.3	2.3	66.5	31,184	27,802
a#2(dp)	0.803	0.791	1.121	0.310	0.225	0.017	0.072	0.002	0.547	0.034	–13.0	62.3	57.8	3,912	0[d]
a#2(sh)	0.838	0.820	1.224	0.248	0.214	0.022	0.085	0.003	0.514	0.041	–13.1	60.0	58.6	4,223	0[d]
G-4	1.254	1.136	1.015	0.166	0.190	0.024	0.138	0.004	0.396	0.066	–9.1	22.0	44.4	12,517	5,808
H-1(Tcp)	0.925	1.005	0.946	0.161	0.178	0.022	0.158	0.005	0.379	0.075	—	19.9	50.0	13,346	7,621
H-1(Tcb)	0.964	1.011	1.088	0.164	0.192	0.016	0.105	0.003	0.397	0.050	–11.4	23.9	52.8	11,832	6,547
H-3	2.219	2.522	1.686	0.155	0.319	0.009	0.072	0.002	0.531	0.034	–4.9	10.5	43.3	18,631	11,721
H-4	1.606	1.465	1.340	0.195	0.260	0.032	0.171	0.005	0.329	0.081	–7.4	11.8	45.0	17,666	11,066
H-5(sample 1)	1.078	1.198	0.950	0.172	0.158	0.016	0.138	0.004	0.446	0.066	–7.4	18.2	46.8	14,084	7,800
H-5(sample 2)	1.081	1.198	0.964	0.172	0.158	0.016	0.138	0.004	0.446	0.066	–10.3	21.4	47.1	12,745	6,514
H-6(bh)	1.547	1.751	1.368	0.214	0.297	0.014	0.085	0.003	0.581	0.041	–7.5	16.3	46.9	14,996	8,745
H-6(Tct)	1.574	1.800	1.862	0.203	0.255	0.011	0.085	0.003	0.564	0.041	–7.3	10.0	54.2	19,035	13,971
H-6(Tcb)	1.577	1.796	2.134	0.209	0.328	0.014	0.092	0.003	0.580	0.044	–7.1	12.4	57.4	17,256	12,665
VH-1(sample 3)	1.265	1.538	1.356	0.282	0.451	0.075	0.118	0.004	0.513	0.056	–8.5	12.2	49.4	17,391	11,562
WT#14	0.800	0.813	1.183	0.231	0.209	0.071	0.329	0.010	0.108	0.156	–12.7	24.1	56.2	11,763	7,000
WT#15	1.196	1.133	1.450	0.339	0.148	0.105	0.302	0.009	0.109	0.144	–11.8	21.6	51.2	12,668	7,136
G-2	0.872	0.855	1.075	0.183	0.135	0.060	0.348	0.010	–0.042	0.166	–11.8	20.5	52.6	13,101	7,791
WT-10	1.634	1.924	1.567	0.220	0.350	0.011	0.072	0.002	0.598	0.034	–6.2	7.3	49.0	21,636	15,742
WT#12	1.370	1.300	1.397	0.220	0.281	0.032	0.171	0.005	0.345	0.081	–8.1	11.4	49.8	17,951	12,188

Table 8 (continued). Results of NETPATH Corrections to Groundwater ^{14}C Ages

Sample	$m_{calcite}$	$m_{Ca/Na}$	m_{CO2}	m_{NaCl}	m_{gypsum}	$m_{dolomite}$	m_{glass}[a]	m_{pyrite}	m_{SiO2}	m_{clay}[b]	$\delta^{13}C$	^{14}A	$^{14}A_0$	Uncorrected ^{14}C age[c] (yr)	Corrected ^{14}C age[c] (yr)
JF#3	0.604	0.596	1.009	0.282	0.277	0.196	0.585	0.018	–0.564	0.278	–8.6	30.7	51.0	9,762	4,189
WT-17	0.954	0.949	1.128	0.181	0.172	0.055	0.171	0.005	0.212	0.081	–8.3	16.2	52.0	15,047	9,647
WT#3	0.989	0.942	1.208	0.169	0.175	0.071	0.256	0.008	0.280	0.122	–8.2	22.3	52.2	12,405	7,025
UZ-14(Tcp)	1.274	1.409	0.798	0.189	0.138	0.015	0.125	0.004	0.413	0.059	–14.1	24.6	38.7	11,593	3,745
UZ-14(Tcb)	1.340	1.482	0.794	0.217	0.138	0.016	0.125	0.004	0.463	0.059	–14.4	21.1	37.4	12,862	4,731
16S/49E-5acc	0.986	0.624	0.988	0.169	0.250	0.130	0.342	0.010	0.158	0.162	–7.1	19.3	44.8	13,599	6,969
15S/49E-22dcc	0.995	0.737	1.211	0.214	0.325	0.121	0.312	0.009	0.017	0.148	–10.2	15.6	50.0	15,359	9,632

DTN: GS930108315213.002, GS930908312323.003, GS950808312322.001, MO0007GNDWTRIS.002, MO0007GNDWTRIS.003, MO0007GNDWTRIS.007, MO0007GNDWTRIS.009, MO0007GNDWTRIS.010, MO0007GNDWTRIS.011, MO0007MAJIONPH.003, MO0007MAJIONPH.005, MO0007MAJIONPH.006, MO0007MAJIONPH.011, MO0007MAJIONPH.012, MO0007MAJIONPH.013, MO0007MAJIONPH.014, (input data for major ions are listed in Table 3)

DTN (output data): LA0006EK12213S.001

[a]Glass composition was defined as: $K_{0.402}Na_{0.368}Ca_{0.023}Fe(3+)_{0.026}Al_{0.7826}Si_{4.190}O_{10.0}$ (Broxton et al. 1987, Table 3, Topopah Spring Member).

[b]Clay composition was defined as: $K_{0.027}Na_{0.127}Ca_{0.164}Mg_{0.245}Fe(3+)_{0.1186}Al_{1.646}Si_{3.434}O_{10.0}$.

[c]Carbon-14 age was calculated from $t_{years} = 8266.6 \ln(^{14}A_0/^{14}A)$, where $^{14}A_0 = 100$ pmc for the uncorrected ages and $^{14}A_0$ was determined by NETPATH for the corrected ^{14}C ages. Corrected ages are based on Assumptions 14, 15, 16 and 17 in Table 4.

[d]The NETPATH model calculated a negative ^{14}C age for this sample.

response to runoff events in the wash (Savard 1994, p. 1805), and recent water samples from borehole a#2 have bomb-pulse levels of chlorine-36 (DTN: LAJF831222AQ98.011), providing confirmation that borehole a#2 is located in an area of active recharge. A number of lines of evidence therefore indicate that, although the ^{14}C activities of groundwater near Yucca Mountain require corrections for the effects of calcite dissolution, the actual value of $^{14}A_0$ in some cases may have been underestimated by the NETPATH models. The effect of using a different $^{14}A_o$ in calculating ^{14}C ages is shown in Table 9 for samples with various pmc values. The true ^{14}C ages for groundwater samples from the volcanic units probably are between the uncorrected ^{14}C ages and the corrected ^{14}C ages calculated, assuming $^{14}A_0$ is 50 pmc.

Table 9. Calculated ^{14}C Ages for Different Assumed Values of Initial ^{14}C Activity ($^{14}A_0$)

Measured ^{14}C Activity (pmc)	^{14}C Age Using $^{14}A_0$ = 100 pmc (yr)	^{14}C Age Using $^{14}A_0$ = 65 pmc (yr)	^{14}C Age Using $^{14}A_0$ = 50 pmc (yr)
5	24,765	21,204	19,035
10	19,035	15,474	13,305
15	15,683	12,122	9,953
20	13,305	9,744	7,575
25	11,460	7,899	5,730
30	9,953	6,392	4,223
35	8,679	5,117	2,949
40	7,575	4,014	1,845
45	6,601	3,040	871
50	5,730	2,169	modern
55	4,942	1,381	modern
60	4,223	662	modern
65	3,561	modern	modern
70	2,949	modern	modern
75	2,378	modern	modern

DTN: N/A

In general terms, the ^{14}C ages calculated for groundwaters in the vicinity of Yucca Mountain are youngest in the northeast (i.e., borehole a#2) and increase to the south-southwest and southwest across Yucca Mountain into Crater Flat. The uncorrected ages increase from approximately 4,000 yr in the northeast to approximately 21,000 yr (borehole WT-10) in the southwest. Ages corrected on the basis of NETPATH calculations including the dissolution of calcite with zero ^{14}C activity range from 0 yr in the northeast (borehole a#2) to approximately 15,000 yr in the southwest (borehole WT-10).

The ^{14}C ages of groundwater samples from wells in or near Fortymile Wash are younger than the ages of groundwaters beneath Yucca Mountain and Crater Flat. The uncorrected ages range from approximately 4,000 yr in the north (borehole a#2) to approximately 10,000 yr in the south (borehole JF#3). Corrected ages range from 0 yr in the north (borehole a#2) to approximately 4,100 yr in the south (borehole JF#3). The sample from well J-13 has slightly older uncorrected and corrected ages (Table 8).

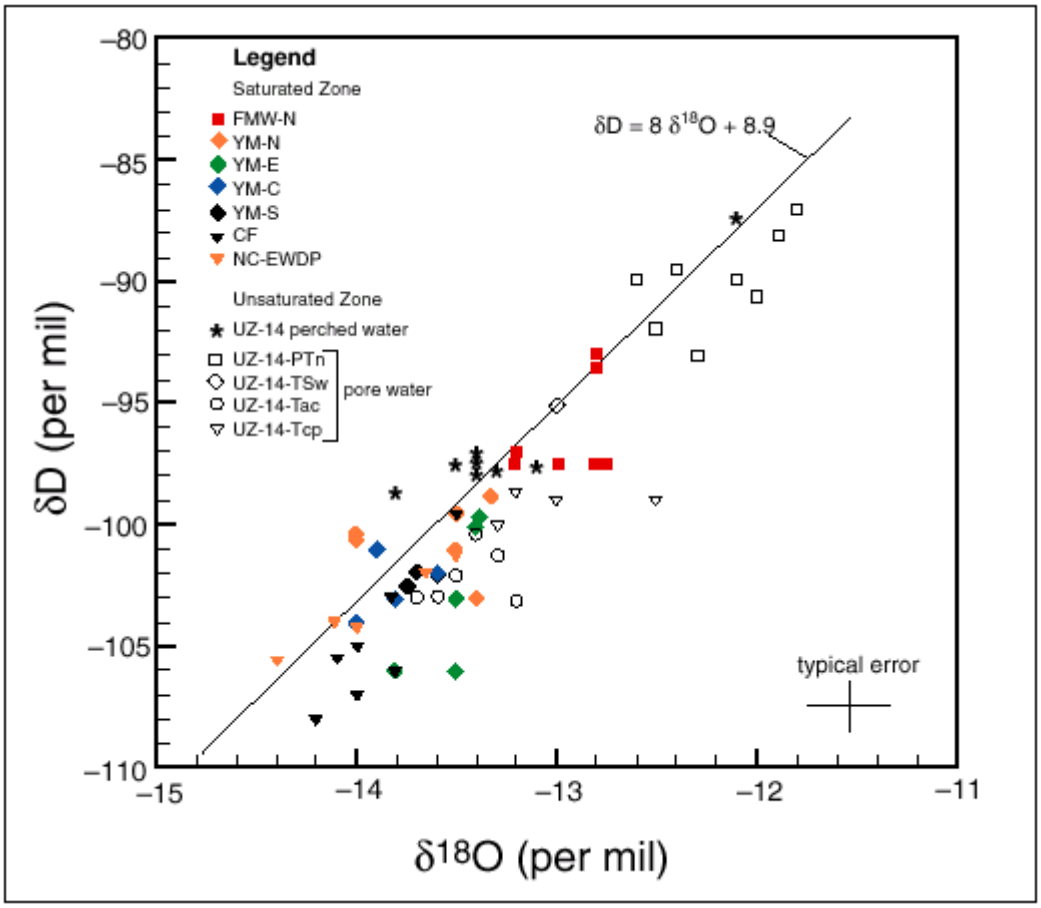
In all, the ^{14}C age calculations suggest groundwaters beneath Yucca Mountain were recharged between 6,000 and and 19,000 yr ago depending on whether corrected or uncorrected ages are used. The δD and $\delta^{18}O$ data are consistent with recharge of these waters during cooler climates than exist in the region today and have existed for approximately the last 10,000 yr. Therefore, the data favor recharge ages between approximately 10,000 and 19,000 yr for groundwaters beneath Yucca Mountain and southern Crater Flat. The groundwaters in Fortymile Wash have ages that range from modern to approximately 10,000 yr. Therefore, these waters were recharged more recently than most groundwaters beneath Yucca Mountain. This conclusion is consistent with the available δD and $\delta^{18}O$ data, which suggest groundwaters in Fortymile Wash (except borehole a#2) were recharged during climates that were cooler than the modern climate but warmer than the climate under which the groundwaters beneath Yucca Mountain were recharged.

A comparison of the ^{14}C ages of the dissolved inorganic and dissolved organic carbon in groundwater from the regional carbonate aquifer has indicated that isotope exchange needs to be considered in addition to dissolution of calcite or dolomite when correcting the ^{14}C ages of the dissolved inorganic carbon in the carbonate aquifer (Thomas 1996, pp. 95–101). Isotope exchange was not considered in applying NETPATH to groundwater samples from the carbonate aquifer at borehole p#1 (Assumption 17) and, therefore, the ^{14}C ages listed in Table 8 for samples from borehole p#1 probably overestimate the true ages. Reaction models that included isotope exchange resulted in a range of corrected ^{14}C ages that included some ages less than 10,000 yr. As originally reported by Thomas (1996, pp. 95–101), the magnitude of the age correction was very sensitive to the amount of carbon assumed to be contributed by isotope exchange and the assumed $\delta^{13}C$ of the carbonate exchanging with the groundwater.

6.5.4.2.2 Carbon-14 Ages of Perched Waters

The same reaction models and assumptions used to correct the ^{14}C ages of the groundwater samples from the regional flow system were also used to correct the ^{14}C ages of some of the perched-water samples reported in Table 7. The corrected ^{14}C ages of the selected perched-water samples, including those from boreholes SD-7 and UZ-14, were generally less than 5,000 yr. However, other observations indicate that the ^{14}C ages of the perched-water samples do not require substantial correction for the dissolution of carbonate. First, the ratios of chlorine-36 to stable chlorine ($^{36}Cl/Cl$) of the perched-water samples were similar to those expected for their uncorrected ^{14}C age, based on reconstructions of $^{36}Cl/Cl$ ratios in precipitation throughout the late Pleistocene and Holocene from pack-rat midden data (Plummer et al. 1997, Fig. 3; DTN: LAJF831222AQ97.002, GS950708315131.003 and GS960308315131.001). Second, Winograd et al. (1992, Fig. 2) presented data from calcite deposits that indicated the $\delta^{18}O$ values in precipitation during the Pleistocene were, on average, 1.9 per mil more depleted during pluvial periods compared to interpluvial periods. The $\delta^{18}O$ values of the perched-water samples generally are more depleted than pore-water samples from the shallow unsaturated zone at Yucca Mountain by more than 1.0 per mil (Figure 23). This consistent difference suggests that, at some boreholes, the perched water may contain a substantial component of water from the Pleistocene.

The lack of agreement between the corrected ^{14}C age determined for the perched-water samples from the NETPATH model and the greater age indicated by the $^{36}Cl/Cl$ and $\delta^{18}O$ data may have



DTN: GS000700012847.001, GS950808312322.001, MO0007GNDWTRIS.002, MO0007GNDWTRIS.003, MO0007GNDWTRIS.005, MO0007GNDWTRIS.006, MO0007GNDWTRIS.007, MO0007GNDWTRIS.008, MO0007GNDWTRIS.009, MO0007GNDWTRIS.010, MO0007GNDWTRIS.012, MO0007GNDWTRIS.013, USGS (n.d.) (see assumption 23 in Table 4), (data are listed in Tables 3 and 7)

NOTE: This figure has color-coded data points and should not be read in a black and white version.

Figure 23. Delta Deuterium and Delta Oxygen-18 Data for Borehole UZ-14 Unsaturated-Zone Pore Water, Perched Water, and Groundwater Near Yucca Mountain

resulted from erroneous assumptions in the NETPATH model regarding the ^{14}C activity of soil-zone calcites; the NETPATH model assumes the soil-zone calcite was completely depleted in ^{14}C (Assumption 14). Another possible reason for underestimated values of $^{14}A_0$ is that the mass-balance approach does not account for the increase in Ca^{2+} and Mg^{2+} due to evapotranspiration of precipitation, an increase that was then erroneously attributed to the dissolution of calcite or dolomite (Assumption 16). In summary, it is tentatively concluded that the uncorrected ^{14}C ages of the perched water calculated from their measured ^{14}C activities approximate their true ^{14}C ages. Based on the ^{14}C activities of perched-water samples in Table 7 and assuming $^{14}A_0$ equals 100 pmc, the ^{14}C ages of the perched-water samples are generally between 7,000 and 11,000 yr, although the single sample from borehole NRG-7a and one of several samples from UZ-14 had much younger ^{14}C ages of about 3,300 yr.

In summary, the available ^{14}C, δD, and $\delta^{18}O$ data for perched waters suggest these waters are older and were infiltrated during climates that were cooler than those under which the shallow unsaturated-zone pore waters were infiltrated.

6.5.5 Evaluation of Evidence for Mixing Relations Between Waters from Different Sources

6.5.5.1 Evaluation of Evidence for Mixing Relations Between Perched Waters at Yucca Mountain and Upgradient Groundwaters

Although it may seem that establishing whether or not mixing is an important process in the Yucca Mountain flow system should be a relatively simple matter, this turns out not to be the case. The problem is that groundwater compositions of mixing end members are not unique and are not constant. That is, instead of there being a limited number of well-defined compositions that mix to form other compositions, the factors that determine groundwater compositions are continuously variable even for conservative constituents. The processes that determine the concentrations of major constituents in groundwaters such as those present at Yucca Mountain include the following:

1. The composition of precipitation

2. Evapotranspiration

3. Precipitation or dissolution of solid phases in the soil zone, the unsaturated zone, or the saturated zone

4. Interaction of waters with the solid phases in soils and rocks (e.g., leaching, sorption)

5. Interaction of waters with any gas phases present (e.g., CO_2 and carbonic acid)

6. Mixing of waters of different compositions.

To determine whether or not mixing (6) has influenced the composition of a given groundwater, the effects of the other five processes listed above must be independently known or quantifiable. The most likely constituents for which this might be possible are conservative constituents such as chloride. This possibility results from the following facts:

a) Chloride minerals involving the major cations are highly soluble. Therefore, precipitation of a solid phase is generally not a factor in determination of the chloride concentration in groundwaters.

b) The aquifer host rocks generally are not a significant source of chloride ions. That is, the concentration of chloride ions in groundwaters are generally not changed by additions from the host rocks, particularly if those host rocks are volcanic rocks at near-surface temperatures (Assumption 9 in Table 4). Factors (a) and (b) combined eliminate factor (3) above from further consideration.

c) Chloride ions do not have much affinity for the solid surfaces present in aquifers. Therefore, chloride ions that are in the water stay in the water. Factors (b) and (c) eliminate factor (4) above from further consideration.

d) The chloride ion is not a volatile species when dissolved in water at ambient temperatures. Therefore, once dissolved in water, chloride ions do not tend to become enriched in any gas phase that may be present. This fact eliminates factor (5) above from further consideration.

If it can be assumed for the sake of argument, that precipitation compositions are adequately known or can be obtained (Assumptions 10 and 12), factor (1) can be eliminated from further consideration. This result leaves factors (2) and (6) as independent variables. If the amount of evapotranspiration associated with a given groundwater composition could be independently determined, then, under certain conditions, mixing relations for groundwaters could be determined from the concentrations of conservative species. Unfortunately, the amount of evapotranspiration represented by a given groundwater composition is commonly inferred from the concentrations of conservative species in the waters. This fact precludes the use of conservative species in the definition of mixing relations unless the amount of evapotranspiration can be independently determined. This determination is usually difficult to do.

One case in which conservative species may allow the definition of mixing relations is the situation in which the number of waters that are mixing is known and there are a sufficient number of conservative species with a sufficient range of concentrations to determine the proportions of each groundwater in the mixture. A possible example of this case could be that in which local recharge at Yucca Mountain mixes into the underflow coming from upgradient sources. Both the recharge water and the underflow water must have well defined and different concentrations of conservative constituents for meaningful mixing relations to be derived. The chloride concentrations in perched waters and groundwaters upgradient of Yucca Mountain (e.g., borehole H-6) show similar ranges (Table 3). Therefore, chloride concentrations cannot be used to define mixing relations for these waters.

Other conservative constituents (e.g., SO_4^{2-}, F^-, U^{6+}, As, Se, δD, and $\delta^{18}O$) may show greater differences in concentrations between perched and upgradient groundwaters at Yucca Mountain and could be used to define mixing relations. For example, if it could be determined that uranium was a conservative constituent in Yucca Mountain perched and groundwaters, a strong candidate for a method to derive the desired mixing proportions would be one involving $^{234}U/^{238}U$ activity ratios and uranium concentrations. For this method to be viable, the uranium activity ratios in each component would have to be different (and separately constant). The uranium concentrations of the two components could either be the same value or two different values. However, the concentrations must be constant and measurable for each component. Unfortunately, the hydrochemical database currently available for the Yucca Mountain area is inadequate to test mixing relations of this type.

6.5.5.2 Implications of Chloride and Deuterium Data for Mixing Between the Carbonate and Volcanic Aquifers

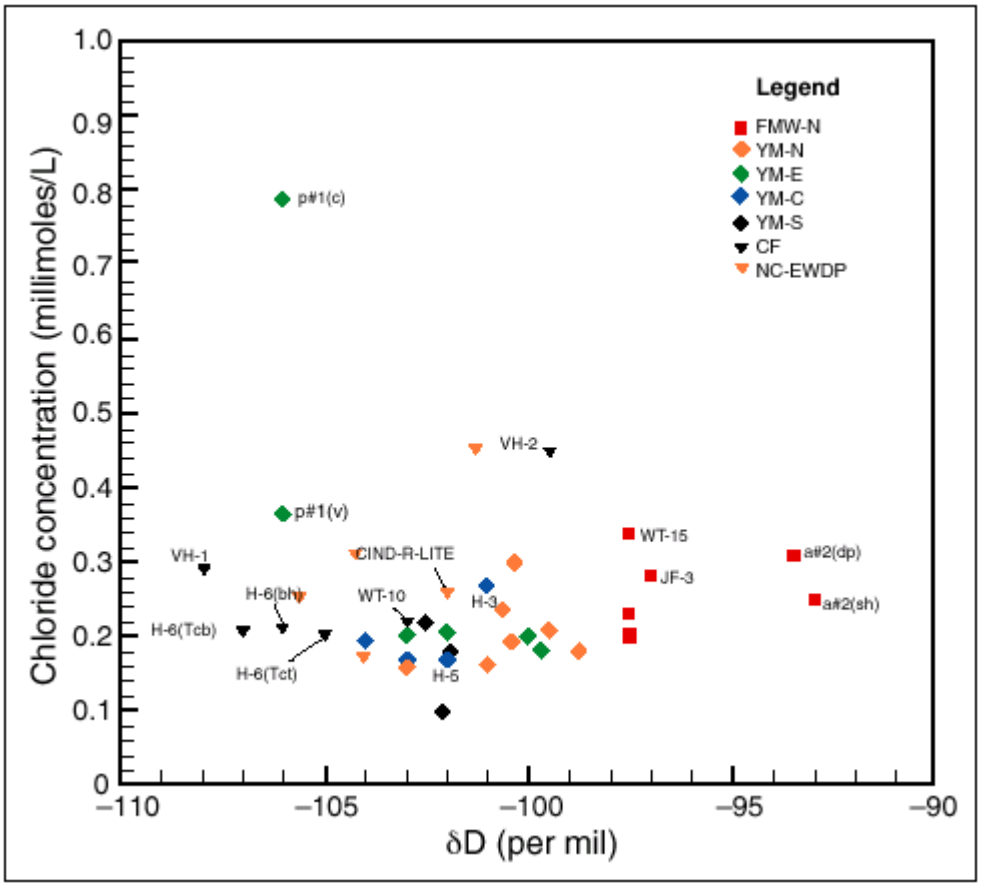
To evaluate the question of upwelling of water from the carbonate aquifer into the volcanic units, Cl^- concentrations were plotted as a function of δD (Figure 24). Chloride and δD were chosen to investigate possible mixing relations because these constituents are relatively conservative once in the groundwater. As the figure shows, groundwater samples from the volcanic units have variable δD values that encompass the δD value of groundwater from the carbonate aquifer, represented by the sample p#1(c). The absence of a large contrast in the δD of groundwater in the volcanic and carbonate aquifers is, in itself, inconclusive with regards to mixing because the δD value of two unrelated groundwaters can be similar if the climate under which recharge occurred was similar. As discussed in the following paragraphs, the large contrast between the Cl^- concentrations of groundwater in the carbonate and volcanic aquifers is far more diagnostic with regard to the extent of mixing between the two aquifers.

Groundwaters in the volcanic units have some variability in Cl^- concentrations, but most of this variability is confined to areas bordering Yucca Mountain in Crater Flat (samples VH-1 and VH-2), the southern edge of Crater Flat (samples NC-EWDP-1D, NC-EWDP-9S, and NC-EWDP-3D), or Fortymile Wash (samples WT-15, JF-3 and 29a#2). Except for sample p#1(v), the groundwater samples in the volcanic aquifer at Yucca Mountain itself have relatively uniform Cl^- concentrations of approximately 0.2 mmol L^{-1} (7 mg L^{-1}). The higher Cl^- concentration of the p#1(v) sample can be explained by mixing between groundwater from the carbonate and volcanic aquifers within the borehole. It is estimated from flow logs that the p#1(v) sample received about 28.6 percent of its water from the carbonate aquifer as a result of upward flow in the borehole, despite an attempt to isolate the volcanic and carbonate aquifers from each other with a temporary plug (Craig and Robison, 1984, p. 49).

The data for sample p#1(c) indicate that groundwater in the carbonate aquifer at Yucca Mountain has a Cl^- concentration nearly four times as high (0.79 mmol L^{-1}, or 28 mg L^{-1}) as that typical for groundwaters in the volcanic aquifer. The representativeness of the Cl^- concentration data for the carbonate aquifer at p#1 was assessed by comparing these data with the Cl^- concentrations of major springs discharging from the carbonate aquifer in Ash Meadows. The Cl^- concentrations at Ash Meadows ranged from 0.59 to 0.76 mmol L^{-1} and had a discharge-weighted average of 0.66 mmol L^{-1} (Winograd and Pearson, 1976, Table 1). Although the Cl^- concentrations of groundwater at p#1 are slightly higher than the groundwater discharging at Ash Meadows, the data for the carbonate aquifer from these two areas are consistent and support the contention that the groundwater in the carbonate aquifer at Yucca Mountain has a much higher Cl^- concentration than groundwater in the volcanic aquifer.

The large contrast in Cl^- concentrations between the volcanic and carbonate aquifers indicates that, unless all the volcanic aquifer water samples were uniformly affected by water from the carbonate aquifer, groundwaters in the volcanic units beneath Yucca Mountain contain, at most, only a minor amount of water from the carbonate aquifer. A uniform response of groundwater Cl^- concentrations in the volcanic aquifer to upwelling from the carbonate aquifer seems unlikely, however, given the variable depths of the groundwater samples and the variability in other chemical and isotopic constituents. The conclusion that upwelling of groundwater from the carbonate aquifer into the volcanic aquifer is minor does assume that the Cl^- concentration of

groundwater sample p#1(c) is representative of the carbonate aquifer in the vicinity of Yucca Mountain (Assumption 11).



DTN: GS000700012847.001, GS950808312322.001, GS970708312323.001, MO0007GNDWTRIS.002, MO0007GNDWTRIS.003, MO0007GNDWTRIS.005, MO0007GNDWTRIS.006, MO0007GNDWTRIS.007, MO0007GNDWTRIS.008, MO0007GNDWTRIS.009, MO0007GNDWTRIS.010, MO0007GNDWTRIS.011, MO0007GNDWTRIS.012, USGS (n.d.) (see assumption 23 in table 4), (data are listed in Tables 3 and 7)

NOTE: This figure has color-coded data points and should not be read in a black and white version.

Figure 24. Chloride Versus Delta Deuterium of Groundwater Near Yucca Mountain

Fridrich et al. (1994, p. 157) hypothesized that the Solitario Canyon Fault could be a conduit for upwelling of water from the carbonate aquifer into the volcanic units overlying it. The groundwater samples obtained near the Solitario Canyon Fault (boreholes H-3, H-5, H-6, WT-10) have low Cl^- concentrations suggesting that they contain little water from the carbonate aquifer (Figure 24). Because the δD contents of groundwater near Fortymile Wash and water from the carbonate aquifer are very different (Figure 24), the slightly elevated Cl^- concentrations of some groundwater samples from the Fortymile Wash area compared to wells on Yucca Mountain were probably not caused by groundwater mixing between the carbonate and volcanic aquifers.

6.5.6 Evaluation of Evidence for the Magnitude of Recharge at Yucca Mountain

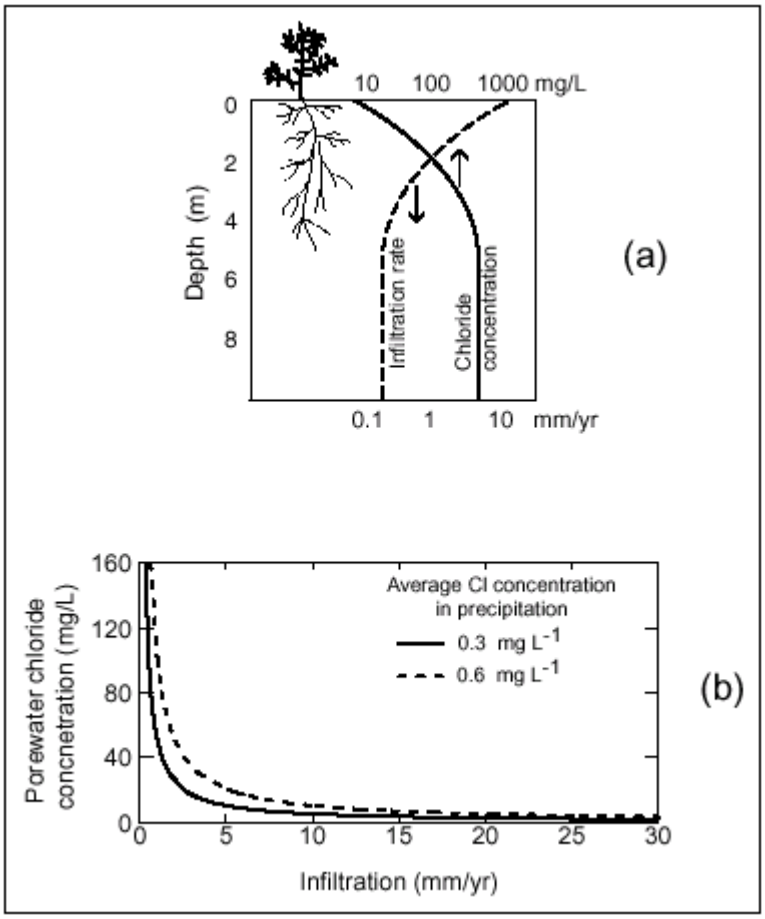
The magnitude of recharge at Yucca Mountain is estimated in this section on the basis of the concentrations of constituents such as chloride that are considered conservative in groundwater systems of the type present at Yucca Mountain (Assumption 9). In particular, the Cl mass balance (CMB) method will be used for this purpose. This method is based on the premise that the flux of Cl deposited at the surface equals the flux of Cl carried beneath the root zone by infiltrating water. With increasing depth in the root zone, Cl concentrations in soil waters increase and apparent infiltration rates decrease as water is extracted by the processes of evapotranspiration (Figure 25). However, once soil waters move below the zone of evapotranspiration, they become net infiltration and their Cl concentrations are assumed to remain constant. It is these Cl concentrations that are used to calculate net infiltration rates and ultimately, recharge rates.

The CMB method uses the following equation to calculate the infiltration rate (I):

$$I = (P\ C_0)/C_p \qquad \text{(Eq. 4)}$$

where P is average annual precipitation, C_0 is average Cl concentration in precipitation, including the contribution from dry fallout, and C_p is the measured Cl concentration in groundwaters. The CMB method (Figure 25) assumes one-dimensional, downward piston flow, constant average annual precipitation rate, constant average annual Cl deposition rate, no run-on or run-off, no Cl source other than precipitation (e.g., it is assumed that the concentrations of Cl brought in by surface runoff and Cl released from weathering of surface rocks are negligible), and no Cl sink.

Estimates of recharge using the CMB technique for 15 groundwater basins in Nevada were found to be in fairly good agreement with estimates obtained by the Maxey-Eakin linear step function (Dettinger 1989, p. 75). Using a 6-year study of two upland basins selected as analog wetter climate sites for Yucca Mountain, Lichty and McKinley (1995, p. 1) showed the CMB method to be more robust than a water-balance modeling approach using a deterministic watershed model for estimating basin-wide recharge for two comparatively wet sites in the Kawich Range north of Yucca Mountain. They attributed the robustness of the CMB method to the small number of measured parameters required as compared to the number of parameters needed for defining a deterministic watershed model.



DTN: N/A–reference only

Note: Part (a) illustrates the underlying basis of the CMB method. Part (b) shows prorewater Cl concentrations as a function of infiltration, assuming a range of chloride deposition rates (106 to 183 mg porewater Cl m^{-2} yr^{-1}). Assuming an average annual precipitation rate of 170 mm, these deposition rates correspond to effective Cl concentrations of 0.62 mg L^{-1} to 1.07 mg L^{-1} in local precipitation.

Figure 25. Chloride Mass Balance Method for Estimating Infiltration

Point estimates of net infiltration or recharge using the CMB method tend to be less robust than basin-wide estimates because of additional assumptions concerning vertical groundwater flow and surface water flow. Conditions under which these assumptions may not be valid at Yucca Mountain are discussed in another AMR (CRWMS M&O 2000, section 6.9.2.2). The applicability of the CMB method to the specific conditions at Yucca Mountain (e.g., fractured rock) is an assumption to be verified (TBV) (Assumption 13). Another TBV assumption is that the annual deposition rate for chloride is known and constant for present-day conditions as well as over the long-term past (Assumption 12). Values of net infiltration estimated at Yucca Mountain using the CMB method range from less than 0.5 mm yr^{-1} in washes to a maximum of nearly 20 mm yr^{-1} beneath ridgetops and sideslopes (based on data and calculations in DTN: LA0002JF831222.001, LA0002JF831222.002, LA9909JF831222.010, LA9909JF831222.012; CRWMS M&O 2000, Sec. 6.9.2.4), depending on the Cl deposition rate assumed in the calculation.

Table 10 lists recharge rates calculated from measured groundwater Cl concentrations using the CMB method. This method requires that the Cl deposition rate, which is the product of precipitation and effective Cl concentration in precipitation (including both wet and dry fallout), be known. The average annual precipitation rate for Yucca Mountain is 170 mm (Hevesi et al. 1992, p. 677), and estimates of average Cl concentrations in precipitation at Yucca Mountain range from 0.3 to 0.6 mg L^{-1} (CRWMS M&O 2000, Sec. 6.9.2.3). To bound the recharge rate estimates, Rate 1 in Table 10 is calculated using the lower estimate for Cl concentration whereas Rate 2 is calculated using the higher estimate. The CMB recharge estimates average 7 ± 1 mm yr^{-1} for Rate 1, and 14 ± 2 mm yr^{-1} for Rate 2 (Table 10). The much narrower range of fluxes estimated for the saturated zone samples compared to the unsaturated zone samples can probably be attributed to the greater volume averaging of the saturated-zone samples, as well as to mixing in the aquifer and in the borehole when the saturated-zone samples were pumped.

Table 10. Recharge Rates Based on the Chloride Mass Balance Method

Well Identifier	Chloride concentration (mg L^{-1})	Apparent Recharge Rate[a] (mm yr^{-1})	
		Rate 1	Rate 2
G-2	6.5	7.8	15.7
UZ-14 (sh)	6.7	7.4	14.8
H-1 (Tcp)	5.7	8.9	17.9
b#1(bh)	10.8	4.7	9.4
c#1	7.4	6.9	13.8
c#2	7.1	7.2	14.4
c#3	7.2	7.1	14.2
c#3('95)	6.5	7.8	15.7
ONC#1	7.1	7.2	14.4
p#1(v)[b]	13.0	3.9	7.8
G-4	5.9	8.6	17.3
H-3	9.5	5.4	10.7
H-4	6.9	7.4	14.8
H-5	6.1	8.4	16.7
UZ#16	10.6	4.8	9.6
WT#12	7.8	6.5	13.1
WT-17	6.4	7.7	15.5
WT#3	6.0	8.2	16.5

DTN: GS950808312322.001, MO0007MAJIONPH.003, MO0007MAJIONPH.004, MO0007MAJIONPH.005, MO0007MAJIONPH.007, MO0007MAJIONPH.011, MO0007MAJIONPH.012, MO0007MAJIONPH.013, (chloride concentrations are listed in Table 3)

NOTE: [a]Rate 1 is calculated using the lower estimate for Cl concentration in precipitation (0.3 mg L^{-1}); Rate 2 is calculated using the higher estimate (0.6 mg L^{-1}). Recharge estimates obtained by the CMB method are based on Assumptions 9, 10, 12 and 13 in Table 4.

[b]Approximately 28.6 percent of the water in this sample is from upward flow in the borehole from the carbonate aquifer (Craig and Robison 1984, p. 49).

6.5.7 Evaluation of Evidence for Downgradient Dilution

The areal distributions of chemical and isotopic constituents shown in figures in Section 6.5.1 and the regional flow paths that were determined from these distributions (Figure 17) suggest that the groundwater can retain its chemical identity over transport distances of at least forty kilometers. Remarkably, the chemical and isotopic identity of the source water appears to be preserved even where regional flow paths converge as groundwater flows toward discharge areas south of the Site-Model boundary (Figure 17). The fact that compositional differences are preserved even where flow lines converge suggests that mixing and dispersion perpendicular to the flow lines is very limited. Therefore, dilution of chemical constituents in groundwaters that flow from the area of the proposed repository is also expected to be very limited.

Locations where dilution of chemical and radiological constituents along potential flowpaths might be expected include the area where groundwaters from beneath the footprint of the proposed repository encounter the groundwaters in Fortymile Wash and the area where groundwaters in Fortymile Wash encounter the groundwaters of the Amargosa Desert. These areas will be discussed separately.

6.5.7.1 Evaluation of Evidence for Dilution of Constituents in Yucca Mountain Groundwaters by Mixing with Groundwaters in Fortymile Wash

The distribution of $^{234}U/^{238}U$ activity ratios shown in Figure 16 indicates that the high activity ratios found in samples from boreholes on Yucca Mountain do not occur in boreholes in Fortymile Wash. Because flowlines based on chloride concentrations feed into Fortymile Wash from the northwest, the high $^{234}U/^{238}U$ activity ratios might be expected to extend to the Fortymile Wash boreholes. One possible reason they do not is that mixing of groundwater from Yucca Mountain with groundwater from further upgradient in Fortymile Wash has decreased the uranium activity ratios in groundwaters in wells J-12, JF#3, and J-13.

If this dilution process does operate as envisioned (i.e., a two-component mixing process), and if uranium acts as a conservative component in the Yucca Mountain and Fortymile Wash groundwaters, the $^{234}U/^{238}U$ activity ratio of the mixture could be derived using the following equation (Faure 1977, p. 98):

$$\left(\frac{^{234}U}{^{238}U}\right)_{mixture} = \frac{[U]_{a\#2}[U]_{WT\#3}\left[\left(\frac{^{234}U}{^{238}U}\right)_{WT\#3} - \left(\frac{^{234}U}{^{238}U}\right)_{a\#2}\right]}{[U]_{mixture}\left([U]_{a\#2} - [U]_{WT\#3}\right)} + \frac{[U]_{a\#2}\left(\frac{^{234}U}{^{238}U}\right)_{a\#2} - [U]_{WT\#3}\left(\frac{^{234}U}{^{238}U}\right)_{WT\#3}}{\left([U]_{a\#2} - [U]_{WT\#3}\right)}$$

(Eq. 5)

The $^{234}U/^{238}U$ activity ratio in a groundwater sample from borehole a#2 is 4.0, and the average uranium concentration is 0.67 (DTN: GS980108312322.003). The water in this well could be used as one end member in the mixing equation. Well WT#3 is the closest well with a high $^{234}U/^{238}U$ activity ratio typical of wells on Yucca Mountain. The water from this well could be used as the other end member in the mixing calculation. Three samples from this well give an average $^{234}U/^{238}U$ activity ratio of 7.2, with a range of 7.207 to 7.283, and an average uranium

concentration of 0.77 ppb, with a range of 0.756 to 0.776 (DTN: GS980908312322.009). A problem exists with choosing the uranium concentration to be used for the mixture. The wells J-12 and JF#3 could logically be considered to be downgradient of wells a#2 and WT#3 and, thereby, be potential candidates for representing the mixed water. However, the uranium concentrations measured for groundwater from the former two wells are 0.3 and 0.8 ppb, respectively. Both of these values are outside the range of uranium concentrations measured in samples of the end-member groundwaters. This fact precludes the use of the mixing equation.

The total range of uranium concentrations in groundwaters identified as potential end members in the mixing problem is 0.3 to 0.8 ppb. Because this range is small, it may be appropriate to assume that uranium concentrations are the same in all the waters involved in the mixing process and use a simpler mixing equation. In the simpler equation, the proportion of each end-member water in the mixture is given by the following:

$$X = \frac{\left(\frac{^{234}U}{^{238}U}\right)_{mixture} - \left(\frac{^{234}U}{^{238}U}\right)_{WT\#3}}{\left(\frac{^{234}U}{^{238}U}\right)_{a\#2} - \left(\frac{^{234}U}{^{238}U}\right)_{WT\#3}} \qquad \text{(Eq. 6)}$$

where X is the fraction of groundwater from borehole a#2 in the mixture. In the two-component mixture, the fraction of groundwater from borehole WT#3 in the mixture would be $1 - X$. The $^{234}U/^{238}U$ activity ratios of groundwater samples from wells JF#3 and J-12 are 4.1 and 5.5, respectively (DTN: GS930108315213.004). If it is assumed that the $^{234}U/^{238}U$ activity ratio for groundwater JF#3 represents the ratio of the mixture, the proportion of a#2 in the mixture would be 0.96. On the other hand, if it assumed that the $^{234}U/^{238}U$ activity ratio for groundwater J-12 represents the ratio of the mixture, the proportion of a#2 in the mixture would be 0.5. These proportions indicate dilution factors of 25 and 2 (or less if the flow path from Yucca Mountain does not extend to Fortymile Wash), respectively, for the WT#3 component.

Interestingly, the $^{234}U/^{238}U$ activity ratios measured in samples of J-13 water over a period of 4 yr range from 5.4 in 1994 to 7.3 in 1997 (DTN: GS960908315215.013, GS980108312322.003). These data suggest groundwater in Fortymile Wash can have a range of $^{234}U/^{238}U$ activity ratios. However, an alternative interpretation of these data is that the large volumes of water pumped from this well over this time interval have drawn high $^{234}U/^{238}U$ activity-ratio groundwater from Yucca Mountain (e.g., WT#3) into the aquifers beneath Fortymile Wash.

Unfortunately, the limited number of data points available for samples from Fortymile Wash make it difficult to more tightly constrain potential mixing/dilution processes between groundwaters from Yucca Mountain and Fortymile Wash using uranium concentrations and isotopic ratios. The data available on other conservative constituents are also inadequate to realistically constrain potential mixing processes.

6.5.7.2 Evaluation of Evidence for Dilution of Constituents in Fortymile Wash Groundwaters by Mixing with Groundwaters and Local Recharge in the Amargosa Valley

As shown in Figure 5, groundwaters with Cl concentrations between 6 and 7 mg L^{-1} are present at the boundary of the Site-Model Area along a continuation of the Fortymile Wash trend with higher concentrations evident in groundwaters to the east and west. This result suggests that there may not be significant dilution of constituents in Fortymile Wash groundwaters as they enter the alluvium in the Amargosa Valley. However, the possibility exists that low Cl concentrations in groundwaters in the Amargosa Valley alluvial aquifer reflect local recharge as well as inflow from upgradient. If local recharge were a significant proportion of groundwaters in Amargosa Valley alluvial aquifer, this should be reflected in the stable isotope, major ion, and ^{14}C data for these groundwaters. These data are discussed in the following sections.

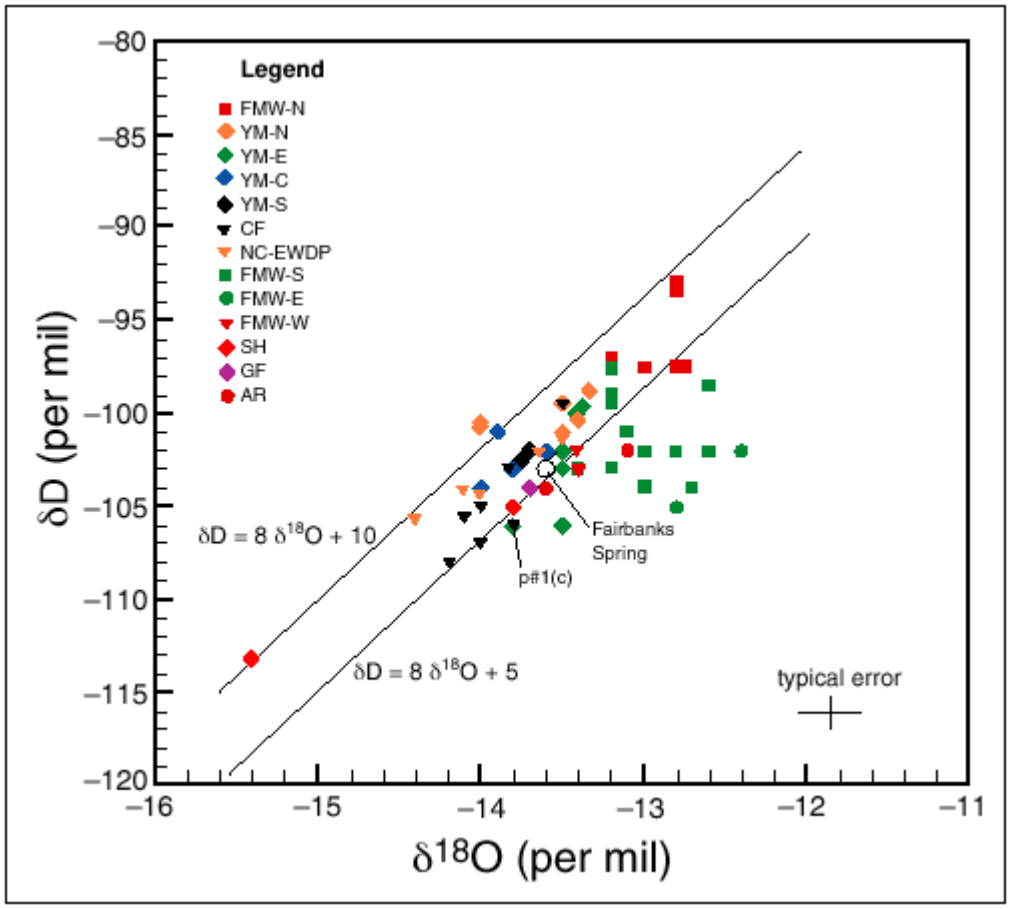
6.5.7.2.1 Evaluation of Evidence from Deuterium and Oxygen-18

A scattergram of the available δD and $\delta^{18}O$ data from the Amargosa Desert and from upgradient areas is shown in Figure 26. Many of the data plot below the present-day global meteoric water line ($\delta D = 8\ \delta^{18}O + 10$) or the Yucca Mountain meteoric water line determined from snow samples ($\delta D = 8\ \delta^{18}O + 8.9$) (Benson and Klieforth 1989, Fig. 14). The most enriched (i.e., least negative) samples are those from Fortymile Wash; the lightest samples are those from Skeleton Hills and Crater Flat.

The δD and $\delta^{18}O$ data help to distinguish the source of the groundwater associated with Fortymile Wash in the Amargosa Desert. The δD values of groundwater near Fortymile Wash in the Amargosa Desert (FMW-S samples in Figure 26) are lower than the δD values of groundwater near Fortymile Wash east of Yucca Mountain (FMW-N samples), suggesting either a different origin or a different age for the groundwater in these two areas. The more depleted δD values associated with Fortymile Wash in the Amargosa Desert may be reflecting a predominantly Pleistocene age of groundwater in the Amargosa Desert. The observation that most of the low chloride groundwater samples from the Amargosa Desert (FMW-S, FMW-W, FMW-E, and SH samples in Figure 26) appear to be associated with a meteoric water line with a smaller deuterium excess ($\delta D = 8\ \delta^{18}O + 5$) than the present-day global or local Yucca Mountain meteoric water lines also may be indicating a predominantly Pleistocene origin for Amargosa Desert groundwater. The value of the deuterium excess decreases with increasing relative humidity in the moisture source area, and relative humidity would be expected to have been higher over the oceans in the Pleistocene, when global temperatures were cooler than at present (Section 6.5.4.1; Clark and Fritz 1997, p. 45; Merlivat and Jouzel 1979, p. 5029).

Data for two samples indicate that groundwater near the Skeleton Hills and Gravity Fault is more depleted in δD and $\delta^{18}O$ than is groundwater near Fortymile Wash. The difference in the δD and $\delta^{18}O$ compositions of groundwater from the Fortymile Wash area in the Amargosa Desert and groundwater near the Skeleton Hills and Gravity Fault areas supports the contention that these groundwaters have different source areas and that groundwater near the Skeleton Hills and Gravity Fault is not simply groundwater from Fortymile Wash that has been chemically modified by interaction with carbonate alluvium near the Skeleton Hills. Unlike major cations and anions, the δD and $\delta^{18}O$ compositions would not be substantially modified by water/rock interaction

with the carbonate alluvium. The δD and $\delta^{18}O$ compositions of groundwater near the Skeleton Hills and Gravity Fault is similar to water from the carbonate aquifer at Yucca Mountain (p#1(c)) and from Fairbanks Spring, the northernmost large spring in Ash Meadows (Figure 26). This observation is consistent with the interpretation that the groundwater in the alluvium near the Skeleton Hills and Gravity Fault is derived from upward leakage from the carbonate aquifer along the fault (Winograd and Thordarson 1975, pp. C84–C85, C112).



DTN: GS000700012847.001, GS950808312322.001, GS970708312323.001, MO0007GNDWTRIS.002, MO0007GNDWTRIS.003, MO0007GNDWTRIS.005, MO0007GNDWTRIS.006, MO0007GNDWTRIS.007, MO0007GNDWTRIS.008, MO0007GNDWTRIS.009, MO0007GNDWTRIS.010, MO0007GNDWTRIS.011, MO0007GNDWTRIS.012, USGS (n.d.) (see Assumption 23 in Table 4)

NOTE: This figure has color-coded data points and should not be read in a black and white version.

Figure 26. Delta Deuterium Versus Delta Oxygen-18 of Groundwater in the Amargosa Desert and in Upgradient Areas

6.5.7.2.2 Evaluation of Evidence from ^{14}C Data

Generally, groundwater in Amargosa Valley alluvium near the Fortymile Wash drainage has ^{14}C activities that range between 10 and 28 pmc (Figure 15). Groundwater near the Skeleton Hills (SH) and Gravity Fault (GF) has ^{14}C activities that are about 10 pmc or less.

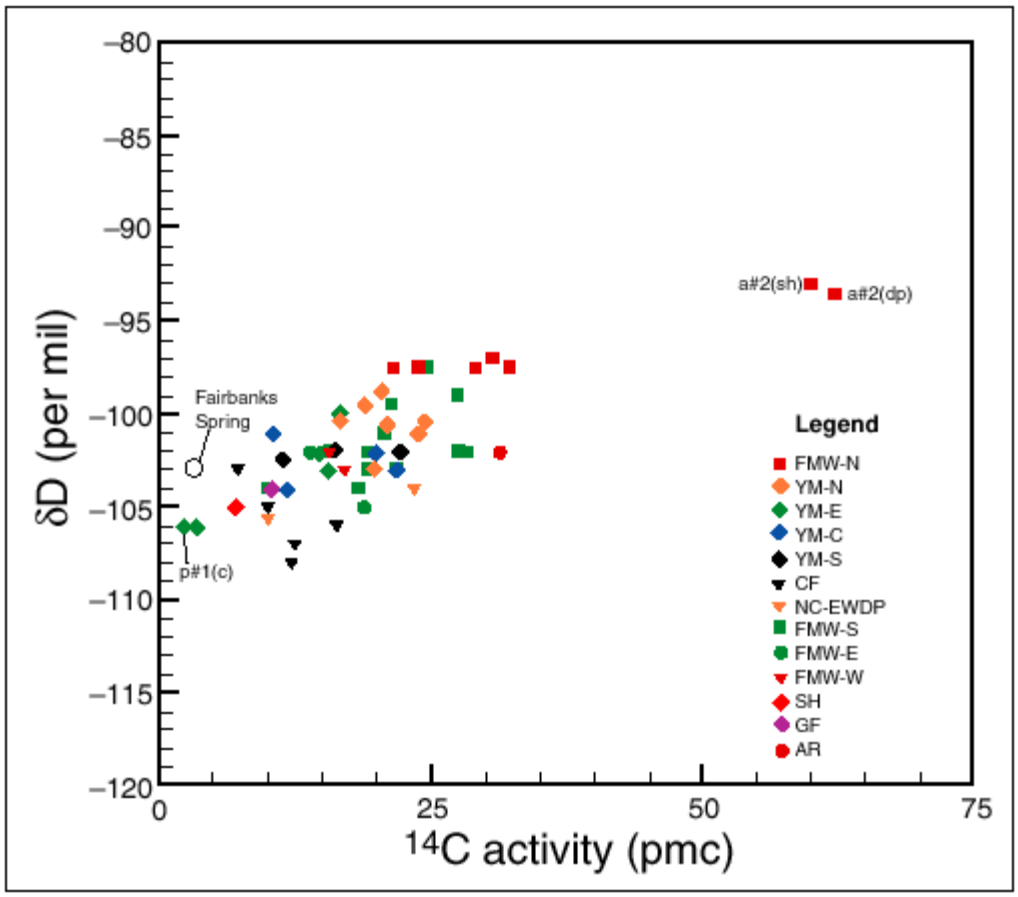
The variable ^{14}C activities of groundwater near Fortymile Wash in the Amargosa Desert were attributed by Claassen (1985, p. F27) to variable distances from surface drainageways, rather

than to variable well depths. In the Amargosa Desert, ^{14}C activities near Fortymile Wash do not show any obvious trend that would indicate that groundwater in the lower reaches of the Wash is older than groundwater beneath its upper reaches, a trend that would be expected if groundwater beneath the lower reaches was derived primarily by southerly groundwater flow beneath the Wash.

Three lines of evidence support the contention that groundwater near the Fortymile Wash in the Amargosa Desert was recharged no later than the early Holocene. First, the uncorrected ^{14}C ages for groundwater samples with ^{14}C activities less than 30 pmc are greater than about 10,000 yr (Table 8), which is consistent with late Pleistocene recharge as the source for the groundwater in the Amargosa Desert. An initial ^{14}C activity ($^{14}A_0$) of about 65 pmc was determined by groundwater samples from borehole a#2, which had bomb-pulse concentrations of tritium and ^{36}Cl but a ^{14}C activity of approximately 62 pmc. Assuming that groundwater in the Amargosa Desert near Fortymile Wash was recharged by water having an initial ^{14}C activity of 65 pmc, the age of Amargosa Desert groundwater near Fortymile Wash is between 7,000 and 15,500 yr. The lower limits of this age range are about 2,000 yr less than the bounding ages for the Fortymile Wash groundwater presented in Claassen (1985, Fig. 15).

A second line of evidence is the association of the δD and $\delta^{18}O$ values of Amargosa groundwater with a paleometeoric water line consistent with a paleoclimate more humid and cooler than the prevailing climate. A related line of evidence is that, for groundwater in the Yucca Mountain area and Amargosa Desert, δD is roughly correlated with ^{14}C activity (Figure 27). The correlation trend supports the hypothesis that groundwater depleted in δD contains a greater fraction of water recharged during the Pleistocene when temperatures were relatively cool than does groundwater enriched in δD.

Finally, the uncorrected ages for the groundwater near Fortymile Wash in the Amargosa Desert are consistent with data from radiocarbon-dated plant assemblages preserved in packrat middens in the Skeleton Hills. These data indicate that wetter conditions in the Amargosa Desert persisted until about 9,300 yr before present, at which time conditions abruptly became more arid (Spaulding and Graumlich 1986, Fig. 3a). The absence of groundwater samples with uncorrected ^{14}C ages less than 9,000 yr supports the contention that recharge has not been important in the Amargosa Desert near Fortymile Wash during the Holocene (Claassen 1985, Fig. 14, p. F27).



DTN: GS930908312323.003, GS950808312322.001, MO0007GNDWTRIS.002, MO0007GNDWTRIS.003, MO0007GNDWTRIS.005, MO0007GNDWTRIS.006, MO0007GNDWTRIS.007, MO0007GNDWTRIS.008, MO0007GNDWTRIS.009, MO0007GNDWTRIS.010, MO0007GNDWTRIS.012, USGS (n.d.) (see Assumption 23 in Table 4)

NOTE: This figure has color-coded data points and should not be read in a black and white version.

Figure 27. Delta Deuterium Versus Carbon-14 Activity of Groundwater in the Amargosa Desert and in Upgradient Areas

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7. SUMMARY AND CONCLUSIONS

Hydrochemical data from the saturated zone in the Yucca Mountain region were compiled, documented, and analyzed in this report. The data were collected over several decades by different organizations, sometimes under less than optimal sampling conditions. Moreover, data are sparse or lacking altogether at critical locations. As a result, the data are subject to multiple interpretations. The following summary includes the favored interpretations, based on the data and analysis in this report. It should be recognized that the acquisition of new data could change the interpretations presented in this report or suggest new interpretations not previously considered. Additionally, various hypotheses suggested by the hydrochemical and isotopic data have yet to be systematically investigated with numerical flow and transport models of the site. A systematic analysis of the hypotheses discussed in this report combined with improved models of the site hydrologic system could change the present understanding of the flow system.

7.1 REGIONAL FLOW PATHS

Areal distributions of chemical and isotopic data were used to constrain flow paths in the region. The analysis traces flow paths by connecting upgradient areas with distinct chemical compositions to downgradient areas with similar chemical compositions. The map of the potentiometric surface was used to guide, but not determine, the selection of which downgradient areas could potentially be linked by a flow path to an upgradient area. Because the flow-path analysis presented assumes that groundwater can be traced in two dimensions, it does not consider the possible effects of local recharge and vertical mixing between aquifers.

Flow paths can be traced using chemistry and isotopes only where compositional differences exist that allow some directions to be eliminated as possible flow directions. Because no single chemical or isotopic species varies sufficiently to determine flow paths everywhere in the study area, multiple chemical and isotopic species were used to construct the flow paths. The flow-path analysis assumed that the δD, $\delta^{18}O$, Cl^-, SO_4^{2-}, Na^+, and Ca^{2+} composition of groundwater along a flow path did not change because of water/rock interaction, recharge of water with a different composition, or vertical mixing between aquifers.

Flow Path 1 shows groundwater moving roughly parallel to the Amargosa River from an area west of Bare Mountain toward the southwest corner of the Site-Model Area (Figure 17). Flow Path 2 indicates that groundwater flows parallel to Fortymile Wash to connect upgradient areas in Fortymile Canyon with downgradient areas in the Amargosa Desert. Groundwater following Flow Path 3 flows from areas in the northwest corner of the Site Model, through central Crater Flat, and then southward to the southern boundary of the Site Model. Groundwater in central Jackass Flats flows southwestward along Flow Path 4, roughly parallel to Fortymile Wash in the vicinity of Amargosa Valley, before turning south-southeast near the southern boundary of the Site-Model Area. Flow Path 5 shows groundwater moving predominantly south-southeast in eastern Crater Flat and then south-southwest after reaching the southern edge of Yucca Mountain. Groundwater from beneath the potential repository area is estimated to flow southeast along Dune Wash (Flow Path 6) toward Fortymile Wash and then south/southwest, or roughly parallel to Fortymile Wash, toward the Amargosa Desert.

The regional flow paths constructed on the basis of the hydrochemical and isotopic data are generally consistent with flow paths that could be inferred from the potentiometric surface but with a stronger north-south component. The stronger north-south component could be reflecting the general north-south structural fabric of the rock, the inability of the method to account for chemical mixing due to recharge or upwelling from the carbonate aquifer, or simply the sparseness of the data in certain regions of the model area.

7.2 EVALUATION OF EVIDENCE FOR LOCAL RECHARGE

Hydrochemical and isotopic data from perched water at Yucca Mountain were compared to similar data from the regional groundwater system at Yucca Mountain to verify whether local recharge is present in the groundwater. The data examined included uranium isotopes ($^{234}U/^{238}U$) and major anions and cations. Based on this comparison, local recharge, as represented by the perched water, was inferred to be a major component in the groundwater beneath Yucca Mountain. Realistic quantification of the percentage of local recharge in groundwater beneath Yucca Mountain is not possible with the currently available hydrochemical database. The conservative position on this issue would be to assume shallow groundwater is composed entirely of local recharge.

7.3 EVALUATION OF EVIDENCE FOR TIMING OF RECHARGE

The timing of recharge at Yucca Mountain as determined by the uncorrected ^{14}C ages of the perched water is predominantly between 11,000 and 7,000 yr before present. However, the possibility exists that even younger recharge may be present in the groundwater beneath Yucca Mountain because of the presence of some perched water with a younger ^{14}C age and the absence of shallow groundwater samples from fault zones and other likely paths for rapid recharge.

Corrections to the ^{14}C ages of groundwater in the vicinity of Yucca Mountain were made using the geochemical code NETPATH, which considers the plausible chemical reactions that may have produced the observed chemistry of the groundwater samples. The corrected ^{14}C ages of the groundwater were approximately one ^{14}C half-life (5715 yr) younger than the uncorrected ^{14}C ages, which were about 22,000 to 18,000 yr in Crater Flat, 14,000 to 12,000 yr in northern Yucca Mountain, 18,000 to 15,000 yr in southern Yucca Mountain, and 13,000 to 9,000 yr beneath Fortymile Wash. Because of the assumption that all the carbon contributed by carbonate dissolution had a ^{14}C activity of 0 pmc and because the model did not consider the increase in Ca^{2+} and Mg^{2+} in soil water due to evaporation in the soil zone, the corrected ^{14}C ages are considered lower limits for the true average age. The true ^{14}C ages probably are bounded by the corrected and uncorrected ^{14}C ages.

The ^{14}C activity of recently recharged groundwater near Fortymile Wash was used to support an estimate for the initial ^{14}C activity of recharge ($^{14}A_0$) of approximately 65 pmc for this setting. This value of $^{14}A_0$ for the Fortymile Wash area is less than the value of 100 pmc previously assumed for that area by Benson and Klieforth (1989, p. 42), which had been based on the ^{14}C activity of calcite-saturated surface runoff in the wash. It is not possible to conclusively reconcile the difference in these two values for $^{14}A_0$. Estimated groundwater ^{14}C ages calculated

with a $^{14}A_0$ value of 65 pmc are approximately 3700 yr younger than the uncorrected ages and are considered to be the best estimate of groundwater ^{14}C ages in the Yucca Mountain area.

7.4 EVALUATION OF EVIDENCE FOR MIXING RELATIONS BETWEEN DIFFERENT WATERS AT YUCCA MOUNTAIN

An evaluation of potential mixing relations among waters in the Yucca Mountain region is important because such mixing could lead to dilution of constituents that might be released to groundwater beneath the potential repository. Unfortunately, proving the occurrence of mixing between two or more groundwaters is a difficult problem. In fact, the available hydrochemical database is inadequate to prove the existence of mixing processes between groundwaters in the Yucca Mountain region beyond a reasonable doubt. To the contrary, the available hydrochemical database can be used to argue that there is minimal mixing between groundwater in the carbonate and volcanic aquifers beneath Yucca Mountain.

7.5 EVALUATION OF EVIDENCE FOR THE MAGNITUDE OF RECHARGE

Estimates of the magnitude of recharge at Yucca Mountain were obtained using the chloride mass balance (CMB) method. This method is simple and appears reliable based on comparisons with other techniques used to estimate the magnitude of recharge. The estimates range from less than 0.5 mm yr^{-1} beneath washes with thick alluvial cover to a maximum of 20 mm yr^{-1} beneath ridge tops and side slopes. For groundwaters within the immediate vicinity of Yucca Mountain, chloride concentrations range from 5 to 9 mg L^{-1}, indicating local recharge rates between 7 and 14 mm yr^{-1}.

7.6 EVALUATION OF EVIDENCE FOR DOWNGRADIENT DILUTION

If groundwater from Yucca Mountain flows toward Fortymile Wash, as suggested by the flow lines drawn on the basis of potentiometric and hydrochemical data, the potential exists for constituents in Yucca Mountain groundwater to be diluted by groundwaters below Fortymile Wash. Uranium concentration and isotope data were used to evaluate this potential dilution process. It was assumed that the uranium concentrations and activity ratios are conservative parameters in the flow systems involved.

The potential for mixing was evaluated using a two-component mixing equation involving the uranium concentration and $^{234}U/^{238}U$ activity ratio. Uranium concentration and isotopic data are available only for five wells in the area of interest, and these data do not allow a unique solution to this mixing equation. In effect, the range in uranium concentrations measured for multiple samples of the mixing end-member groundwaters is similar to the total range of uranium concentrations observed for the full set of groundwater analyses. If it is assumed that the uranium concentrations in the end-member groundwaters are the same in the mixing process, then the mixing proportions are only a function of the differences in the uranium activity ratios. Under this assumption, the estimated proportions of the Fortymile Wash component in the mixture range from 0.5 to 0.9 depending on which downgradient groundwater (from borehole J-12 or JF#3) is used to represent the mixed water.

The areal plot of chloride concentrations in groundwaters within the model boundary suggests that low chloride concentrations typical of groundwaters beneath Yucca Mountain and Fortymile Wash extend to wells at the southern boundary of the model area. This observation, in turn, suggests there would be minimal dilution of constituents that may be present in upgradient groundwaters by mixing with groundwaters within alluvium of the Amargosa Valley.

An alternative interpretation is that the low chloride concentrations found in some Amargosa Valley wells reflect local recharge. In this case, dilution of constituents in upgradient waters by mixing with groundwaters in Amargosa Valley alluvium is a viable process. However, the viability of this interpretation is brought into question by data that suggest the groundwaters in Amargosa Valley alluvium are as old or older than groundwaters at Yucca Mountain. If these groundwaters had a large component of local recharge, they would be expected to have relatively young ages. On the other hand, the available age data would be consistent with the idea that these waters are largely composed of flow from upgradient sources north of Amargosa Desert (i.e., from Fortymile Wash) or with paleorecharge along Fortymile Wash in the Amargosa Desert itself.

7.7 RECOMMENDATIONS

The analyses presented in this report have highlighted the need for particular types of data in certain areas. A sampling strategy that would reduce uncertainty in key elements of the conceptual model of groundwater flow in the Yucca Mountain area is outlined in this section.

7.7.1 Upgradient Sampling Locations

Groundwater beneath Yucca Mountain seems to be composed of water from several sources. Local recharge and groundwater flow from the north or west remain likely possibilities. Local recharge (as represented by perched water) and shallow groundwater in the north, as represented by samples from borehole G-2, are dilute with respect to Cl^- and SO_4^{2-}, have high $(Ca^{2+} + Mg^{2+})/(Na^+ + K^+)$ ratios and low Na^+ concentrations, and are enriched in δD, $\delta^{18}O$, and ^{14}C compared to most groundwater samples from Yucca Mountain. A second source of groundwater, more concentrated in Cl^- and SO_4^{2-}, with lower $(Ca^{2+} + Mg^{2+})/(Na^+ + K^+)$ ratios and higher Na^+ concentrations and with greater depletion of δD, $\delta^{18}O$ and ^{14}C compared to the first source, is also present at Yucca Mountain. Groundwater in Crater Flat has many of the characteristics of the second source. The sample from borehole G-2, the sole groundwater sample in northernmost Yucca Mountain, originated from the relatively shallow Calico Hills Formation. Deep groundwater, from the Prow Pass and Bullfrog Tuffs, has not been sampled in northern Yucca Mountain, and its chemical and isotopic characteristics are unknown. We propose that borehole WT-6 in Yucca Wash be extended from its present depth in the Calico Hills Formation through the Bullfrog Tuff to evaluate the chemical and isotopic characteristics of deep groundwater in northernmost Yucca Mountain.

7.7.2 Local Recharge Sampling

Most existing groundwater samples were obtained by pumping boreholes from intervals that were open to flow over a large range of depths. Frequently, flow logs taken during pumping

indicated that inflow to the boreholes was over widely separated, discrete intervals. Despite possible groundwater mixing during sampling, the existing samples suggest that local recharge may be present in groundwater beneath Yucca Mountain. To further examine this hypothesis, and to better determine the extent and character of local recharge at Yucca Mountain, it is proposed that shallow groundwater be sampled from the vicinity of faults, where focussed recharge may be present. Borehole WT-2 is a strong candidate for sampling because of its location within the potential repository area and because it intersects the water table near the Ghost Dance Fault. Borehole WT-1 is also a strong candidate for sampling because of its proximity to the Dune Wash Fault and its location downgradient from the potential repository area. Both of these boreholes are open to the saturated zone only within a few tens of meters of the water table and local recharge, if present, would have a good chance of being detected.

7.7.3 Discrete Interval Sampling

One conceptual model of flow of groundwater at Yucca Mountain is that local recharge pushes underflow from areas upgradient of Yucca Mountain deeper into the flow system. In this model, both local and upgradient sources of recharge remain in their respective flow tubes and do not undergo much mixing. Mixing that seems to be evident in trends exhibited by the groundwater samples is, in this model, mostly or entirely attributed to mixing in the borehole during pumping. Chemical and isotopic trends, or the lack thereof, are attributed by this model to the effects of sampling variable amounts of groundwater from flow tubes containing groundwater from different sources. It is proposed that groundwater samples be collected in existing and planned deep boreholes, such as those drilled as part of the NC-EWDP, in such a way as to maximize the chances of detecting compositional differences between groundwater in shallow and deep zones.

7.7.4 Fault Plane Sampling

Groundwater sampled from near faults in southern Yucca Mountain at the NC-EWDP boreholes and CIND-R-LITE Well is similar in composition to groundwater in Crater Flat, an observation that suggests groundwater from the potential repository area is not moving southwestward under the fault-block ridges in southernmost Yucca Mountain. Groundwater samples from existing and planned boreholes located along these faults would provide valuable additional evidence to evaluate this hypothesis. Of existing wells, borehole WT-11 is favorably situated to help in this evaluation and groundwater samples from this borehole would also be useful in narrowing existing gaps in areal coverage. Some future boreholes should be located so as to directly sample groundwater from faults in southern Yucca Mountain.

* * *

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8.2 CODES, STANDARDS, REGULATIONS, AND PROCEDURES

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8.3 SOFTWARE

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8.4 SOURCE DATA, LISTED BY DATA TRACKING NUMBER

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GS920408312321.002. Flowmeter (Tracejector) Survey on Test Wells in Permeable Zones in Yucca Mountain Area. Submittal date: 04/27/1987.

GS920508312321.004. Chemical Analyses of Water from Selected Wells and Springs in the Yucca Mountain Area, Nevada and Southeastern California. Submittal date: 05/28/1992.

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GS930108315213.004. Uranium Isotopic Analyses of Groundwaters from SW Nevada – SE California. Submittal date: 01/21/1993.

GS930308312323.001. Chemical Composition of Groundwater and the Locations of Permeable Zones in the Yucca Mountain Area. Submittal date: 03/05/1993.

GS930908312323.003. Hydrochemical Data from Field Test and Lab Analyses of Water Samples Collected at Field Stations: USW VH-1, JF3, UE-29 UZN#91, Virgin Spring, Nevares Spring, UE-25 J#12, UE-25 J#13, UE-22 ARMY#1, and USW UZ-14. Submittal date: 09/30/1993.

GS950708315131.003. Woodrat Midden Age Data in Radiocarbon Years Before Present. Submittal date: 07/21/1995.

GS950808312322.001. Field, Chemical, and Isotopic Data Describing Water Samples Collected in Death Valley National Monument and at Various Boreholes in and Around Yucca Mountain, Nevada, Between 1992 and 1995. Submittal date: 08/16/1995.

GS951208312272.002. Tritium Analyses of Porewater from USW UZ-14. Submittal date: 00/00/0000. URN-0527

GS960208315215.001. Uranium and Thorium Isotope Data Determined by Mass Spectrometry for Dating Sub-Surface Secondary Deposits from ESF and Drill Hole Locations. Submittal date: 02/21/1996.

GS960308315131.001. Woodrat Midden Radiocarbon (C14) . Submittal date: 03/07/1996.

GS960908315215.013. Uranium and Thorium Isotope Data for Waters Collected Between January 1994 and September 1996. Submittal date: 09/25/1996.

GS960908315215.014. Uranium and Thorium Isotope Data for ESF Secondary Minerals Collected Between March 1996 and July 1996. Submittal date: 09/25/1996.

GS970208315215.001. Uranium and Thorium Isotope Data Collected Between September 1996 and February 1997 from Secondary Minerals in the ESF. Submittal date: 03/06/1997.

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GS970708312323.001. Delta 18-O and Delta D Stable Isotope Analyses of a Bore-Hole Waters from GEXA Well 4 and VH-2. Submittal date: 07/22/1997.

GS970808315215.012. Uranium and Thorium Isotope Data from Secondary Minerals in the ESF Collected Between 02/15/97 and 09/15/97. Submittal date: 09/17/1997.

GS980108312322.003. Uranium Isotopic Data for Saturated- and Unsaturated-Zone Waters Collected Between December 1996 and December 1997. Submittal date: 01/29/1998.

GS980108312322.005. Water Chemistry Data from Samples Collected at Borehole USW WT-24, Between 10/06/97 and 12/10/97. Submittal date: 01/26/1998.

GS980208312322.006. Uranium Isotopic Data for Saturated- and Unsaturated-Zone Waters Collected by Non-YMP Personnel Between May 1989 and August 1997. Submittal date: 02/03/1998.

GS980908312322.008. Field, Chemical, and Isotopic Data from Precipitation Sample Collected Behind Service Station in Area 25 and Ground Water Samples Collected at Boreholes UE-25 C #2, UE-25 C #3, USW UZ-14, UE-25 WT #3, UE-25 WT #17, and USW WT-24, 10/06/97 to 07/01/98. Submittal date: 09/15/1998.

GS980908312322.009. Uranium Concentrations and 234U/238U Ratios from Spring, Well, Runoff, and Rain Waters Collected from the Nevada Test Site and Death Valley Vicinities and Analyzed Between 01/15/1998 and 08/15/1998. Submittal date: 09/23/1998.

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LA0002JF831222.001. Apparent Infiltration Rates in Alluvium from USW UZ-N37, USW UZ-N54, USW UZ-14 and UE-25 UZ#16, Calculated by Chloride Mass Balance Method. Submittal date: 02/25/2000.

LA0002JF831222.002. Apparent Infiltration Rates in PTN Units from USW UZ-7A, USW UZ-N55, USW UZ-14, UE-25 UZ#16, USW NRG-6, USW NRG-7A, and USW SD-6, SD-7, SD-9 and SD-12 Calculated by the Chloride Mass Balance Method. Submittal date: 02/25/2000.

LA9909JF831222.010. Chloride, Bromide, Sulfate, and Chlorine-36 Analyses of ESF Porewaters. Submittal date: 09/29/1999.

LA9909JF831222.012. Chloride, Bromide, and Sulfate Analyses of Porewater Extracted from ESF Niche 3566 (Niche #1) and ESF 3650 (Niche #2) Drillcore. Submittal date: 09/29/1999.

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LAJF831222AQ97.002. Chlorine-36 Analyses of Packrat Urine. Submittal date: 09/26/1997.

LAJF831222AQ98.011. Chloride, Bromide, Sulfate and Chlorine-36 Analyses of Springs, Groundwater, Porewater, Perched Water and Surface Runoff. Submittal date: 09/10/1998.

MO0007GNDWTRIS.002. Isotopic Content of Groundwater from Yucca Mountain Project Borehole, USW G-2, Extracted from ANL-NBS-HS-000021, Geochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing and Recharge at Yucca Mountain, Nevada. Submittal date: 07/27/2000. Submit to RPC URN-0496

MO0007GNDWTRIS.003. Isotopic Content of Groundwater from Yucca Mountain Project Boreholes UZ-14, WT-17, and WT #3, Extracted from ANL-NBS-HS-000021, Geochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing and Recharge at Yucca Mountain, Nevada. Submittal date: 07/27/2000. Submit to RPC URN-0497

MO0007GNDWTRIS.004. Isotopic Content of Groundwater from Borehole TW-5, Extracted from ANL-NBS-HS-000021, Geochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing and Recharge at Yucca Mountain, Nevada. Submittal date: 07/27/2000. Submit to RPC URN-0498

MO0007GNDWTRIS.005. Isotopic Content of Groundwater from Yucca Mountain Project Borehole JF #3, Extracted from ANL-NBS-HS-000021, Geochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing and Recharge at Yucca Mountain, Nevada. Submittal date: 07/28/2000. Submit to RPC URN-0499

MO0007GNDWTRIS.006. Isotopic Content of Groundwater from Selected Yucca Mountain Project WT Boreholes, Extracted from ANL-NBS-HS-000021, Geochemical and Isotopic

Constraints on Groundwater Flow Directions, Mixing and Recharge at Yucca Mountain, Nevada. Submittal date: 07/28/2000. Submit to RPC URN-0500

MO0007GNDWTRIS.007. Isotopic Content of Groundwater from Yucca Mountain Project Boreholes WT #14, WT #15, and WT #12, Extracted from ANL-NBS-HS-000021, Geochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing and Recharge at Yucca Mountain, Nevada. Submittal date: 07/28/2000. Submit to RPC URN-0501

MO0007GNDWTRIS.008. Isotopic Content of Groundwater from Yucca Mountain Project Borehole UE-25 p#1 Extracted from ANL-NBS-HS-000021, Geochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing and Recharge at Yucca Mountain, Nevada. Submittal date: 07/28/2000. Submit to RPC URN-0502

MO0007GNDWTRIS.009. Isotopic Content of Groundwater from Selected Yucca Mountain Project Boreholes Extracted from ANL-NBS-HS-000021, Geochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing and Recharge at Yucca Mountain, Nevada. Submittal date: 07/28/2000. Submit to RPC URN-0503

MO0007GNDWTRIS.010. Isotopic Content of Groundwater from Selected Yucca Mountain Project Boreholes Extracted from ANL-NBS-HS-000021, Geoochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing and Recharge at Yucca Mountain, Nevada. Submittal date: 07/28/2000. Submit to RPC URN-0516

MO0007GNDWTRIS.011. Isotopic Content of Groundwater from Selected Boreholes Not Drilled for the Yucca Mountain Project Extracted from ANL-NBS-HS-000021, Geochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing and Recharge at Yucca Mountain, Nevada. Submittal date: 07/28/2000. Submit to RPC URN-0517

MO0007GNDWTRIS.012. Isotopic Content of Groundwater from NC-EWDP Boreholes, Extracted from ANL-NBS-HS-000021, Geochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing and Recharge at Yucca Mountain, Nevada. Submittal date: 07/28/2000. Submit to RPC URN-0504

MO0007GNDWTRIS.013. Isotopic Content of Perched Groundwater from Yucca Mountain Project Boreholes Extracted from ANL-NBS-HS-000021, Geochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing and Recharge at Yucca Mountain, Nevada. Submittal date: 07/28/2000. Submit to RPC URN-0505

MO0007MAJIONPH.002. Major Ion Content of Groundwater from Borehole TW-5 Extracted from ANL-NBS-HS-000021, Geochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing and Recharge at Yucca Mountain, Nevada. Submittal date: 07/27/2000. Submit to RPC URN-0506

MO0007MAJIONPH.003. Major Ion Content of Groundwater from Yucca Mountain Project Borehole USW G-2, Extracted from ANL-NBS-HS-000021, Geochemical and Isotopic

Constraints on Groundwater Flow Directions, Mixing and Recharge at Yucca Mountain, Nevada. Submittal date: 07/27/2000. Submit to RPC URN-0507

MO0007MAJIONPH.004. Major Ion Content of Groundwater from Borehole ONC #1, Extracted from ANL-NBS-HS-000021, Geochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing and Recharge at Yucca Mountain, Nevada. Submittal date: 07/27/2000. Submit to RPC URN-0508

MO0007MAJIONPH.005. Major Ion Content of Groundwater from Boreholes UZ-14, WT-17, and WT #3, Extracted from ANL-NBS-HS-000021, Geoochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing and Recharge at Yucca Mountain, Nevada. Submittal date: 07/27/2000. Submit to RPC URN-0509

MO0007MAJIONPH.006. Major Ion Content of Groundwater from Selected Boreholes Not Drilled on the Yucca Mountain Project, Extracted from ANL-NBS-HS-000021, Geochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing and Recharge at Yucca Mountain, Nevada. Submittal date: 07/25/2000. Submit to RPC URN-0510

MO0007MAJIONPH.007. Major Ion Content of Groundwater from Yucca Mountain Project Borehole UE-25 UZ #16, Extracted from ANL-NBS-HS-000021, Geochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing and Recharge at Yucca Mountain, Nevada. Submittal date: 07/27/2000. Submit to RPC URN-0511

MO0007MAJIONPH.008. Major Ion Content of Groundwater from Selected YMP and Other Boreholes Extracted from ANL-NBS-HS-000021, Geochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing and Recharge at Yucca Mountain, Nevada. Submittal date: 07/27/2000. Submit to RPC URN-0512

MO0007MAJIONPH.009. Major Ion Content of Groundwater from Borehole NDOT Extracted from ANL-NBS-HS-000021, Geochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing and Recharge at Yucca Mountain, Nevada. Submittal date: 07/27/2000. Submit to RPC URN-0518

MO0007MAJIONPH.010. Major Ion Content of Groundwater from Borehole UE-25 p #1 Extracted from ANL-NBS-HS-000021, Geochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing and Recharge at Yucca Mountain, Nevada. Submittal date: 07/27/2000. Submit to RPC URN-0519

MO0007MAJIONPH.011. Major Ion Content of Groundwater from Selected Yucca Mountain Project Boreholes Extracted from ANL-NBS-HS-000021, Geochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing and Recharge at Yucca Mountain, Nevada. Submittal date: 07/27/2000. Submit to RPC URN-0520

MO0007MAJIONPH.012. Major Ion Content of Groundwater from Selected YMP and Other Boreholes Extracted from ANL-NBS-HS-000021, Geochemical and Isotopic Constraints on

Groundwater Flow Directions, Mixing and Recharge at Yucca Mountain, Nevada. Submittal date: 07/27/2000. Submit to RPC URN-0521

MO0007MAJIONPH.013. Major Ion Content of Groundwater from Selected YMP and Other Boreholes Extracted from ANL-NBS-HS-000021, Geoochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing and Recharge at Yucca Mountain, Nevada. Submittal date: 07/27/2000. Submit to RPC URN-0522

MO0007MAJIONPH.014. Major Ion Content of Groundwater from Selected Boreholes Not Drilled on the Yucca Mountain Project Extracted from ANL-NBS-HS-000021, Geochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing and Recharge at Yucca Mountain, Nevada. Submittal date: 07/27/2000. Submit to RPC URN-0523

MO0007MAJIONPH.015. Major Ion Content of Groundwater from NC-EWDP Boreholes Extracted from ANL-NBS-HS-000021, Geochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing and Recharge at Yucca Mountain, Nevada. Submittal date: 07/27/2000. Submit to RPC URN-0524

MO0007MAJIONPH.016. Major Ion Content of Perched Groundwater from Selected YMP Boreholes with Perched Water Extracted from ANL-NBS-HS-000021, Geochemical and Isotopic Constraints on Groundwater Flow Directions, Mixing and Recharge at Yucca Mountain, Nevada. Submittal date: 07/28/2000. Submit to RPC URN-0525

MO0008MAJIONPH.017. Major Ion Content of Groundwater from Selected WT Boreholes Drilled for the Yucca Mountain Project, Extracted from ANL-NBS-HS-000021, Geochemical and Isotopic Constraints on Major Ion Concentrations and pH from Table 3 of AMR ANL-NBS-HS-000021. Submittal date: 08/01/2000. Submit to RPC URN-0526

MO9907YMP99025.001. YMP-99-025.01, List of Boreholes. Submittal date: 7/19/1999.

8.5 OUTPUT DATA, LISTED BY DATA TRACKING NUMBER

LA0006EK12213S.001. NETPATH Model Results for Yucca Mountain Groundwater Carbon-14 Age Corrections. Submittal date: 06/05/2000.