Regional Assessment of Aquifers for Thermal Energy Storage

Volume 1

Prepared for Pacific Northwest Laboratory
Seasonal Thermal Energy Storage Program
under Subcontract B-93966-A-O

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

The views, opinions and conclusions contained in this report are those of the contractor and do not necessarily represent those of the United States Government or the United States Department of Energy.

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
Under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

Price: Printed Copy \$ _____ *: Microfiche \$3.00

*Pages	NTIS
	Selling Price
001-025	\$4.00
026-050	\$4.50
051-075	\$5.25
076-100	\$6.00
101-125	\$6.50
126-150	\$7.25
151-175	\$8.00
176-200	\$9.00
201-225	\$9.25
226-250	\$9.50
251-275	\$10.75
276-300	\$11.00

REGIONAL ASSESSMENT OF AQUIFERS
FOR THERMAL ENERGY STORAGE

VOLUME 1
REGIONS 1 THROUGH 6

Century West Engineering Corporation
Spokane, Washington

June 1981

Prepared for
Pacific Northwest Laboratory
Seasonal Thermal Energy Storage Program
Under Subcontract B-93966-A-0
Under U.S. Department of Energy Contract
DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Richland, Washington 99352

TABLE OF CONTENTS

<u>VOLUME 1</u>	<u>Pages</u>
INTRODUCTION	1-1 - 1-23
REGION 1 - WESTERN MOUNTAIN RANGES	1-1 - 1-47
Introduction	1-1 - 1-3
Geologic Framework	1-3 - 1-19
Hydrogeologic Framework	1-20 - 1-29
Major Aquifers	1-30
Aquifers Unsuitable for ATES	1-31 - 1-38
Aquifers Suitable for ATES	1-39 - 1-41
Region's ATES Potential	1-42
References Cited	1-43 - 1-44
General References	1-45 - 1-47
REGION 2 - ALLUVIAL BASINS	2-1 - 2-33
Introduction	2-1
Geologic Framework	2-1 - 2-9
Hydrogeologic Framework	2-9 - 2-16
Major Aquifers	2-17
Aquifers Unsuitable for ATES	2-18 - 2-21
Aquifers Suitable for ATES	2-22 - 2-27
Region's ATES Potential	2-28
References Cited	2-29 - 2-30
General References	2-31 - 2-33
REGION 3 - COLUMBIA LAVA PLATEAU	3-1 - 3-31
Introduction	3-1 - 3-3
Geologic Framework	3-4 - 3-15
Hydrogeologic Framework	3-15 - 3-24
Major Aquifers	3-25
Aquifers Unsuitable for ATES	3-26 - 3-30
Region's ATES Potential	3-31
References Cited	3-32 - 3-33
General References	3-34 - 3-37
REGION 4 - COLORADO PLATEAU	4-1 - 4-12
Introduction	4-1
Geologic Framework	4-1
Hydrogeologic Framework	4-2 - 4-4
Major Aquifers	4-5
Aquifers Unsuitable for ATES	4-6 - 4-9
Region's ATES Potential	4-10
References Cited	4-11
General References	4-12

TABLE OF CONTENTS (Continued)

	<u>Pages</u>
REGION 5 - HIGH PLAINS	5-1 - 5-36
Introduction	5-1 - 5-3
Geologic Framework	5-3 - 5-13
Hydrogeologic Framework	5-14 - 5-21
Major Aquifers	5-22 - 5-23
Aquifers Unsuitable for ATES	5-24 - 5-27
Aquifers Suitable for ATES	5-28 - 5-31
Region's ATES Potential	5-32
References Cited	5-33 - 5-34
General References	5-35 - 5-36
REGION 6 - GLACIATED CENTRAL REGION	6-1 - 6-42
Introduction	6-1 - 6-3
Geologic Framework	6-3 - 6-9
Hydrogeologic Framework	6-9 - 6-23
Major Aquifers	6-24
Aquifers Unsuitable for ATES	6-25 - 6-29
Aquifers Suitable for ATES	6-29 - 6-38
Region's ATES Potential	6-39
References Cited	6-40 - 6-41
General References	6-42
<u>VOLUME 2</u>	
REGION 7 - UNGLACIATED CENTRAL REGION	7-1 - 7-62
Introduction	7-1 - 7-3
Geologic Framework	7-4 - 7-16
Hydrogeologic Framework	7-17 - 7-32
Major Aquifers	7-33
Aquifers Unsuitable for ATES	7-34 - 7-43
Aquifers Suitable for ATES	7-44 - 7-49
Region's ATES Potential	7-50
References Cited	7-51 - 7-55
General References	7-56 - 7-62
REGION 8 - UNGLACIATED APPALACHIANS	8-1 - 8-25
Introduction	8-1
Geologic Framework	8-3 - 8-6
Hydrogeologic Framework	8-6 - 8-13
Major Aquifers	8-14
Aquifers Unsuitable for ATES	8-15 - 8-17
Aquifers Suitable for ATES	8-18 - 8-21
Region's ATES Potential	8-22
References Cited	8-23 - 8-24
General References	8-25

TABLE OF CONTENTS (CONTINUED)

	<u>Pages</u>
REGION 9 - GLACIATED APPALACHIANS	9-1 - 9-27
Introduction	9-1
Geologic Framework	9-2 - 9-6
Hydrogeologic Framework	9-6 - 9-15
Major Aquifers	9-16
Aquifers Unsuitable for ATES	9-17 - 9-19
Aquifers Suitable for ATES	9-20 - 9-23
Region's ATES Potential	9-24
References Cited	9-25
General References	9-26 - 9-27
REGION 10 - COASTAL PLAIN	10-1 - 10-39
Introduction	10-1 - 10-3
Geologic Framework	10-4 - 10-16
Hydrogeologic Framework	10-17 - 10-25
Major Aquifers	10-26
Aquifers Unsuitable for ATES	10-27 - 10-29
Aquifers Suitable for ATES	10-30 - 10-33
Region's ATES Potential	10-34
References Cited	10-35 - 10-36
General References	10-37 - 10-39
REGION 11 - HAWAII	11-1 - 11-18
Introduction	11-1 - 11-2
Geologic Framework	11-2 - 11-3
Hydrogeologic Framework	11-3 - 11-6
Major Aquifers	11-7 - 11-12
Aquifers Unsuitable for ATES	11-13 - 11-15
Region's ATES Potential	11-16
References Cited	11-17
General References	11-18
REGION 12 - ALASKA	12-1 - 12-29
Introduction	12-1 - 12-2
Geologic Framework	12-3
Hydrogeologic Framework	12-3 - 12-14
Major Aquifers	12-15 - 12-18
Aquifers Unsuitable for ATES	12-19 - 12-22
Aquifers Suitable for ATES	12-23 - 12-26
Region's ATES Potential	12-27
References Cited	12-28
General References	12-29
<u>VOLUME 3</u>	
APPENDICES	
Appendix A -	List of Aquifers A-1 - A-23
Appendix B -	Aquifer Data B-1 - B-109

LIST OF FIGURES

<u>FIGURE NUMBER</u>	<u>FIGURE TITLE</u>	<u>PAGE NUMBER</u>
1-1	Major Ground-Water Regions of the United States, Excepting Alaska and Hawaii	1-2
1-2	Small System Limiting Guidelines	1-8
1-3	Large System Limiting Guidelines	1-9
1-1	Outline of Region 1 Showing Six Major Provinces	1-2
1-2	Major Geographic Areas as Referenced in Text	1-6
1-3	Major Aquifers Unsuitable for ATEs in Region 1	1-32
1-4	Major Aquifers Suitable for ATEs in Region 1	1-40
2-1	Outline of Region 2	2-2
2-2	Diagrammatic Cross Section of Ground-Water Flow Regime in Coastal Valleys	2-11
2-3	Major Aquifers Unsuitable for ATEs in Region 2	2-19
2-4	Major Aquifers Suitable for ATEs in Region 2	2-23
3-1	Outline of Region 3	3-2
3-2	Regional Columbia River Basalt Group Stratigraphic Nomenclature	3-8
3-3	Outcrop Extent of the Columbia River Basalt Group	3-9
3-4	Distribution of Formations within the Columbia River Basalt Group	3-11
3-5	Major Sub-Basins in the Columbia Plateau	3-13
3-6	Map of Southern Idaho Showing Snake River Plain Aquifer	3-14
3-7	Major Aquifers Unsuitable for ATEs in Region 3	3-27
4-1	Outline of Region 4 with the Major Aquifers	4-3
4-2	Major Aquifers Unsuitable for ATEs in Region 4	4-7
5-1	Region 5 General Outline	5-2
5-2	Geologic Formations and their Water-Bearing Properties, Northern High Plains	5-4

<u>FIGURE NUMBER</u>	<u>FIGURE TITLE</u>	<u>PAGE NUMBER</u>
5-3	Geologic Formations and their Water-Bearing Properties, Southern High Plains	5-5
5-4	Major Aquifers Unsuitable for ATEs in Region 5	5-25
5-5	Major Aquifers Suitable for ATEs in Region 5	5-29
6-1	Region 6 General Outline	6-2
6-2	General Distribution of Paleozoic, Mesozoic and Cenozoic and Precambrian Rocks	6-5
6-3	Region 6 Generalized Structural Framework	6-8
6-4	Location of the Buried Mahomet River Valley and Buried Abandoned Channel of the Mississippi River	6-11
6-5	Major Aquifers Unsuitable for ATEs in Region 6	6-26
6-6	Major Aquifers Suitable for ATEs in Region 6	6-31
7-1	General Outline of Region 7	7-2
7-2	Regional Structural Features	7-5
7-3	Stratigraphic Correlation Chart for the Powder River Basin-Black Hills Area	7-13
7-4	Stratigraphic Nomenclature of South Dakota	7-14
7-5	Stratigraphic Nomenclature of Mesozoic Era in South Dakota	7-15
7-6	Major Aquifers Unsuitable for ATEs in Region 7	7-35
7-7	Major Aquifers Suitable for ATEs in Region 7	7-45
8-1	Major Physiographic Divisions of Region 8	8-2
8-2	Sketch of Idealized Geologic and Hydrogeologic Conditions in the Blue Ridge Province	8-10
8-3	Sketch of Idealized Geologic and Hydrogeologic Conditions in the Valley and Ridge Province	8-12
8-4	Major Aquifers Unsuitable for ATEs in Region 8	8-16
8-5	Major Aquifers Suitable for ATEs in Region 8	8-20
9-1	Major Physiographic Divisions of Region 9	9-3

<u>FIGURE NUMBER</u>	<u>FIGURE TITLE</u>	<u>PAGE NUMBER</u>
9-2	Distribution of Major Aquifers in Region 9	9-7
9-3	Major Aquifers Unsuitable for ATEs in Region 9	9-18
9-4	Major Aquifers Suitable for ATEs in Region 9	9-21
10-1	Geologic Provinces in Region 10	10-2
10-2	Structural Features of the Gulf Coastal Plain	10-5
10-3	Mississippi Embayment	10-6
10-4	General Correlation of Stratigraphic Units	10-8
10-5	Generalized Geologic Cross Section of Coastal Plain Aquifers	10-9
10-6	Gulf Coastal Plain Correlation of Stratigraphic Units	10-11
10-7	Correlation of the Atlantic Coastal Plain Stratigraphic Units	10-16
10-8	Major Aquifers Unsuitable for ATEs in Region 10	10-28
10-9	Major Aquifers Suitable for ATEs in Region 10	10-31
11-1	Major Aquifers in Region 11	11-8
11-2	Major Aquifers Unsuitable for ATEs in Region 11	11-14
12-1	Region 12 Generalized Distribution of Permafrost	12-5
12-2	Major Aquifer with ATEs Potential in Region 12	12-17
12-3	Major Aquifers Unsuitable for ATEs in Region 12	12-20
12-4	Major Aquifers Suitable for ATEs in Region 12	12-24

LIST OF TABLES

APPENDIX A

<u>TABLE NUMBER</u>	<u>TABLE TITLE</u>	<u>PAGE NUMBER</u>
1-1	Region 1 - List of Aquifers	A-1
2-1	Region 2 - List of Aquifers	A-2 - A-12
3-1	Region 3 - List of Aquifers	A-13
4-1	Region 4 - List of Aquifers	A-14
5-1	Region 5 - List of Aquifers	A-15
6-1	Region 6 - List of Aquifers	A-16
7-1	Region 7 - List of Aquifers	A-17
8-1	Region 8 - List of Aquifers	A-18
9-1	Region 9 - List of Aquifers	A-19
10-1	Region 10 - List of Aquifers	A-20 - A-21
11-1	Region 11 - List of Aquifers	A-22
12-1	Region 12 - List of Aquifers	A-23

APPENDIX B

1-2	Region 1 - Aquifer Data	B-1 - B-9
2-2	Region 2 - Aquifer Data	B-10 - B-24
3-2	Region 3 - Aquifer Data	B-25 - B-33
4-2	Region 4 - Aquifer Data	B-34 - B-36
5-2	Region 5 - Aquifer Data	B-37 - B-41
6-2	Region 6 - Aquifer Data	B-42 - B-50
7-2	Region 7 - Aquifer Data	B-51 - B-59
8-2	Region 8 - Aquifer Data	B-60 - B-65
9-2	Region 9 - Aquifer Data	B-66 - B-71
10-2	Region 10 - Aquifer Data	B-72 - B-97
11-2	Region 11 - Aquifer Data	B-98 - B-103
12-2	Region 12 - Aquifer Data	B-104 - B-109

Introduction

The work presented within this report is part of the Seasonal Thermal Energy Storage (STES) Program which is managed by the Pacific Northwest Laboratory for the United States Department of Energy. The STES program is intended to demonstrate the storage and retrieval of energy on a seasonal basis. Under the STES program, Aquifer Thermal Energy Storage (ATES) systems will be designed, constructed and operated. Part of the STES program is to complete a compendium of existing information. A sub-task involves the collection and summarization of STES-related information on regional aquifers. The goal of the study, and the subject of this report, is to qualitatively describe the ATES potential of the major aquifers throughout the United States. This report is a precursor to the site-specific aquifer studies and is a first step in demonstrating the feasibility of implementing ATES technology.

PROJECT APPROACH

SCOPE

The regional scope of this project involves accumulating existing hydrologic data for the major aquifers and tabulating this data for the following regions: 1) Western Mountain Ranges; 2) Alluvial Basins; 3) Columbia Lava Plateau; 4) Colorado Plateau; 5) High Plains; 6) Glaciated Central region; 7) Unglaciated Central region; 8) Unglaciated Appalachians; 9) Glaciated Appalachians; 10) Atlantic and Gulf Coastal Plain; 11) Hawaii; 12) Alaska (Figure 1-1). For the purpose of

- 1 Western Mountain Ranges
- 2 Alluvial Basins
- 3 Columbia Lava Plateau
- 4 Colorado Plateau
- 5 High Plains
- 6 Glaciated Central Region
- 7 Unglaciated Central Region
- 8 Unglaciated Appalachians
- 9 Glaciated Appalachians
- 10 Coastal Plain

MAJOR GROUND-WATER REGIONS OF THE UNITED STATES, EXCEPTING ALASKA AND HAWAII

Source: Johnson 1966, page 48

FIGURE 1-1

this study, a major aquifer is defined as an aquifer that has established a consistent, sustained, typical yield of at least 50 gallons per minute to a single well. As a result of this study, the major water-bearing rock formations of each region are identified and defined, selected regional aquifers are then evaluated for their individual ATES potential, and hydrologic data are tabulated on a regional basis and referenced with respect to a regional bibliography. Owing to the regional scope of this study, small local aquifers are not covered by this report, but may have potential for ATES. Small, sub-regional, aquifers may be particularly suited for a small-scale ATES system. Furthermore, the aquifers identified in this report as generally suitable for ATES may be unsuitable for ATES at some localities. Likewise, aquifers which are identified as generally unsuitable for ATES may be suitable for ATES at some localities.

The scope of work was organized into four major tasks and appropriate sub-tasks. The major tasks include: 1) a literature search and development of a bibliography for references applicable to aquifer evaluation; 2) aquifer data collection, storage, and tabulation; 3) preparation of the draft report; 4) preparation of the final report.

Task I

The initial phase of the project involved a literature search for all references describing the general hydrologic framework of a region, and references providing specific hydrologic information indicative of an aquifer's potential for ATES. The most available and applicable publications from each state and from the United States Geological Survey were ordered and reviewed. A bibliography was developed to document all publications reviewed. The bibliography is organized by ground-water

region, and the format is that of the United States Geological Survey. Initially, the most general hydrogeologic publications were sought and the most recent publications were selected. Once the hydrogeologic framework was established, all references specific to aquifers were then reviewed.

During Task I, a computer program was developed and utilized for data storage and tabulation. The output from this program included an averaging of aquifer data when several inputs were made for one aquifer. These output tables are appended to the final report and in addition to providing specific aquifer data, also serve to associate the bibliography references to those references in the data tabulation.

Prior to beginning actual data analysis and aquifer evaluation, it was necessary to establish limiting guidelines for aquifer parameters and properties. The selected guidelines and their application to ATES evaluations were derived through discussions with the STES project personnel of the Pacific Northwest Laboratory and after review of current literature on ATES experimental projects. The established guidelines are flexible and are intended to serve as a means of tentatively evaluating each aquifer's potential for ATES. They do not necessarily preclude any aquifer from future development of its ATES potential. The guidelines used for aquifer evaluations are discussed in the next section of this chapter.

Task II

Task II involved the actual gathering and reviewing of data from specific references identified in Task I. The data that were gathered and reviewed were limited to the following quantitative and qualitative

items: 1) transmissivity; 2) storativity; 3) well yield; 4) specific capacity; 5) hydraulic conductivity; 6) storage; 7) flow velocity; 8) hydraulic gradient; 9) porosity; 10) areal extent; 11) depth below surface; 12) boundaries, lateral unit; 13) spatial variation; 14) thickness of aquifer; 15) lithology of aquifer; 16) integrity of upper and lower confining units - 17) geometry (shape); 18) lithology of upper and lower confining units - 19) temperature; 20) thermal conductivity; 21) aquifer upper confinement; 22) aquifer lower confinement; 23) total dissolved solids; 24) hardness; 25) specific conductance; 26) pH; 27) Ca & Mg; 28) Na & K; 29) Cl; 30) SO_4 ; 31) NO_3 ; 32) Fe; 33) fluoride; 34) silicates; 35) age of geologic unit.

The tabulated data in Appendix B contain only those data presented in the specific reference which is cited. The tabulated data do not contain quantitative information derived from manipulating an author's data. The only calculated information presented is the values averaged by the computer. The program averages values when more than one reference cites data for a specific aquifer characteristic. This method of tabulating data and citing the reference from which the data were derived allows for acknowledgement of the source and reveals the data source so additional information may be obtained for future use.

The data gathered for each aquifer were evaluated with respect to the guidelines established during Task I. Use of the guidelines helped determine whether each major aquifer in a region was suitable or unsuitable for ATES. The data were stored and presented for only those aquifers with some potential for ATES. Each of the aquifers that appear to have some ATES potential were generally evaluated with respect

to three different types of storage: low temperature ($>60^{\circ}\text{C}$ $<95^{\circ}\text{C}$); high temperature ($>95^{\circ}\text{C}$ $<150^{\circ}\text{C}$); and chill ($>0^{\circ}\text{C}$ $<10^{\circ}\text{C}$). Evaluations were made for both large and small yield systems.

Task III

Task III involved the preparation of a draft report. This task began with the outlining of a report format to include all 12 regional reports, an introduction to the project and the appended tabulated data. The format and content of the draft report was then reviewed by the STES program staff at the Pacific Northwest Laboratory.

Task IV

Task IV involved the preparation of a final report. The preparation included the final drafting of all regional maps, the completion of a bibliography for each region and the final copy of computer tables. The resulting product is the final report presented herein which contains: an introduction to the project and to the evaluation guidelines; a summary of each region and the information obtained; and an evaluation of those aquifers with ATEs potential.

AQUIFER EVALUATION GUIDELINES

The establishment of limiting guidelines for evaluating an aquifer's ATEs potential was a necessary part of this project and comprised the major portion of Task I. The guidelines established and presented herein were used for development of this report and are preliminary. These general guidelines will most likely be adjusted in light of site-specific information obtained from ATEs testing facilities. Also, the

guidelines are only intended to indicate an aquifer's possible ATES potential.

The development of these guidelines had one basic and common assumption and that was the full penetration of the aquifer by the injection well. This assumption was necessary in order to apply the standard equations used for evaluating an aquifer. The aquifer's properties were separated into four general categories for the purpose of discussion only. In reality, the application of ATES to a specific groundwater flow system will require balancing the complex interaction of all these properties so the mechanical system design will be compatible with the aquifer characteristics and result in the economic recovery of the stored thermal mass.

The guidelines separate an aquifer's properties and its measured parameters into the following four categories: 1) physical properties of the aquifer; 2) hydrodynamic properties; 3) thermodynamic properties; and 4) geochemical properties. The limiting guidelines associated with quantifiable properties are presented in Figures 1-2 and 1-3.

AQUIFER PHYSICAL PROPERTIES

These properties reflect the in-situ state of the aquifer and also affect the shape of the stored thermal mass. The thermal mass shape is indirectly a prime consideration because it is one of the factors influencing the overall economy of the thermal energy recovery operation. The amount of thermal energy recovered depends, in part, upon the heat loss rate of the stored mass. Heat loss is a result of conduction or convection of heat from the surface area of the mass. Therefore, the surface area-to-volume ratio (A_s/V) has a major influence on heat loss

SMALL SYSTEM LIMITING GUIDELINES

* Values near 20000 for Transmissivity are desirable

AQUIFER CHARACTERISTICS	UNITS	CHILL			LOW TEMPERATURE			HIGH TEMPERATURE		
		UNSUITABLE	MARGINAL	SUITABLE	UNSUITABLE	MARGINAL	SUITABLE	UNSUITABLE	MARGINAL	SUITABLE
Depth	Feet	< 20	—	> 20	< 20	—	> 20	< 20	—	Sufficient Hydrostatic Pressure
Thickness	Feet	< 20	>20 <25	>25 <100	< 20	>20 <25	>25 <100	< 20	>20 <25	>25 <100
Typical Well Yield	gpm	< 50	—	>50 <500	< 50	—	>50 <500	< 50	—	>50 <500
Transmissivity	gpd / ft	<1000 or >20,000	—	>1000 or <20,000 *	< 1000 or > 20,000	—	>1000 or < 20,000 *	<1000 or >20,000	—	>1000 or < 20,000 *
Porosity	%	< 5	>5 <15	> 15	< 5	>5 <15	> 15	< 5	>5 <15	> 15
Thermal Conductivity	BTU/ft. - Hr. - F°	< .50	—	.50 - 2.0	< .50	4.1 - 8.0	.50 - 2.0	> 8.0	4.1 - 8.0	2.1 - 4.0

FIGURE 2

LARGE SYSTEM LIMITING GUIDELINES

* Values near 20,000 for Transmissivity are desirable

AQUIFER CHARACTERISTICS	UNITS	CHILL			LOW TEMPERATURE			HIGH TEMPERATURE		
		UNSUITABLE	MARGINAL	SUITABLE	UNSUITABLE	MARGINAL	SUITABLE	UNSUITABLE	MARGINAL	SUITABLE
Depth	Feet	< 20	—	> 20	< 20	—	> 20	< 20	—	Sufficient Hydrostatic Pressure
Thickness	Feet	< 100	—	≥ 100	< 100	—	≥ 100	< 100	—	≥ 100
Typical Well Yield	gpm	< 500	—	> 500	< 500	—	> 500	< 500	—	> 500
Transmissivity	gpd / ft	< 1000	—	> 1000 *	< 1000	—	> 1000 *	< 1000	—	> 1000 *
Porosity	%	< 5	> 5 < 15	> 15	< 5	> 5 < 15	> 15	< 5	> 5 < 15	> 15
Thermal Conductivity	BTU/ft. - Hr. - F°	< .50	2.1 - 4.0	.50 - 2.0	< .50	2.1 - 4.0	.50 - 2.0	> 8.0	4.1 - 8.0	2.1 - 4.0

FIGURE 1-3

rates. The ideal surface area-to-volume ratio is that of a sphere; for this shape the surface area is at a minimum for a given volume. However, a spherical shape would be impossible to achieve in light of the fully penetrating injection well assumption. Therefore, the preferred stored mass configuration is that of a right circular cylinder with the well bore serving as the major vertical axis. To achieve this shape the injected fluid and its thermal energy must have radially symmetric movement away from the well bore. This movement is controlled, in part, by the physical properties of the aquifer matrix.

To achieve the ideal radially symmetric fluid movement, certain media properties must be the same in all directions. If a medium has properties at any point that are the same in all directions emanating from that point the medium is said to be isotropic. If a certain property changes with direction from a point, then anisotropic conditions exist.

If, within the medium, the conditions of isotropy/anisotropy vary from point to point then the medium is said to be heterogeneous. If the conditions of isotropy/anisotropy remain the same at various points within the medium then the medium is said to be homogeneous. The conditions of homogeneity often change because of a change in the medium's composition.

If the condition of varying isotropy/anisotropy is continuous throughout the medium, the medium is said to exhibit trending heterogeneity. The property of discontinuous heterogeneity exists when the degree of isotropy/anisotropy is dependent upon the position of a point within the medium.

A completely homogeneous and isotropic aquifer would most likely allow the desired stored mass shape of a right circular cylinder to form. However, a completely isotropic medium, without other controlling conditions, may not be entirely desirable because of freedom of thermal mixing that may reduce recovery efficiency. So certain compromises must be made in the ideal shape in order to enhance recovery efficiency.

To contain the thermal mass, anisotropic conditions are desirable. Often, the anisotropic conditions existing in an aquifer result in the vertical permeability versus the horizontal permeability differing by two to five times (as measured by hydraulic conductivity). If an aquifer's ATES potential is going to benefit from anisotropy, the horizontal to vertical permeability difference should be greater than normal, perhaps by one order of magnitude (ten times larger). However, the actual permeability must be within a reasonably low range to have an overall desirable effect.

In contrast to the beneficial aspects of anisotropy, the property of heterogeneity may limit an aquifer's ATES potential. This may be particularly true for widely varying heterogeneity or discontinuous heterogeneity, which may result in excess lateral distortion of the stored mass shape. However, gradual or trending heterogeneity may have some beneficial aspects in controlling the stored mass shape, restricting the stored mass shape, and restricting the distance traveled.

The other properties or conditions of the medium (aquifer matrix) discussed in this section have a much smaller role in determining the stored mass shape. The aquifer's lithologic and stratigraphic position, such as its thickness, depth, areal extent, boundary conditions and

degree of confinement, also play a part in the evaluation of an aquifer's ATEs potential.

To allow a stored thermal mass to assume a preferred shape and to enhance thermal energy recovery, it may be ideal for the aquifer's thickness to be at least one order of magnitude less than its areal extent. However, given that there is adequate areal extent, partially penetrating wells can be used to create a suitable storage zone in an aquifer that is very thick. Generalized values for suitable aquifer thickness are provided in Figures I-2 and I-3. The aquifer thickness guidelines apply specifically to the area affected by an operating ATEs facility.

Similar reasoning can be adopted when considering an aquifer's boundary conditions. That is, within an operating area of an ATEs facility, an aquifer's restricted boundary would reduce the recovery efficiency by adversely affecting the stored mass shape or by obstructing movement to the recovery point.

Other aquifer characteristics to be considered relate to depth and confinement. An aquifer's depth is not, by itself, a limiting factor. The guideline of a 20-foot depth is mainly to assure an insulating condition for the thermal mass, although the majority of major aquifers do occur at depths greater than 20 feet. For high temperature storage, adequate depth is needed to provide sufficient hydrostatic pressure so that the liquid phase of the injection fluid may be maintained. For high temperature storage it is also important to have a substantial, thick, confining unit (aquiclude) so that the injection fluids will not breach the confining layer and the energy be lost.

One of the most important physical properties of an aquifer is the type of aquifers porosity. Primary porosities are those pores or voids in the rock matrix that exist as a result of the initial deposition or formation of the geologic unit. Secondary porosities are those resulting from activity after the rock matrix was initially formed or deposited. Secondary porosities are often structurally controlled, such as joints and faults, or chemically controlled, such as solution cavities. In either case, secondary porosities are undesirable because of their somewhat random and unpredictable volumes of stored water. Both factors would adversely affect the stored mass shape and its movement.

Hydrodynamic Properties

The rate and direction of fluid movement within a porous medium (aquifer) are determined by a few characteristics or measured parameters. The quantitative values of these parameters is often determined by aquifer pumping tests and measured yield data. These parameters are actual measurements of the interaction of the physical properties mentioned in the previous section and therefore indirectly affect the stored mass shape by determining its direction and rate of movement.

The first hydrodynamic property to be considered is the hydraulic conductivity (K) or, when considering the aquifer's full thickness, the characteristic of transmissivity. By definition an aquifer's transmissivity is the volume rate of water which will move through the cross-sectional area of a saturated vertical column of the aquifer matrix, which extends the full aquifer thickness with a width of one foot under a hydraulic gradient of one foot per foot. Expressed in United States practical units, this is commonly written as gallons per day per foot.

This characteristic is most often unique to each aquifer because it is a measure of the interaction of all the aquifer's matrix and fluid properties. Transmissivity values are commonly obtained from analysis of aquifer pumping test data, but they can also be derived from flow net data.

The interaction of aquifer properties resulting in a particular aquifer's transmissivity value tend to complicate the use of transmissivity values as a limiting guideline for aquifer selection. However, generally a transmissivity value of 1,000 gallons per day per foot is a minimum, whereas 20,000 gallons per day per square foot is the desirable order of magnitude. This transmissivity value would allow substantial well yields (approximately 1,000 gallons per minute) and still retain a balance of other aquifer properties allowing economic thermal mass recovery. The other aquifer properties mentioned are those directly interacting to produce the transmissivity value and include the porosity, flow velocity, permeability (measured as hydraulic conductivity) and the hydraulic gradient. The interaction is shown by the following equations:

$$V = K (i/n) \text{ and } T = K (b)$$

Where:

V = average pore velocity (laminar flow); feet per day

K = hydraulic conductivity; gallons per day per foot squared

i = hydraulic gradient; feet per foot

n = intrinsic porosity; dimensionless

T = transmissivity; gallons per day per foot

b = aquifer thickness; feet

With the underlying purpose of storing energy in a fluid, the rate of movement of that fluid is a prime consideration. The fluid velocity or pore velocity (V) is influenced by all three factors on the right side of the above equation. Porosity is a ratio expressed as a percent of the void space volume per total volume of a given substance. However, this represents the intrinsic porosity, whereas the flow is most influenced by the effective porosity, which is a measure of the interconnectiveness of the void spaces. The difference between intrinsic and effective porosity is greatest for materials such as clays which do not transmit water. Since this report deals with materials that do transmit water, the difference between intrinsic and effective porosities will not be discussed here. Generally, porosity values are seldom found in the literature and are often estimates obtained from grain-size analysis of unconsolidated sediments (intrinsic porosity) or calculated from pumping transmissivity values (effective porosity) obtained for "water-table" aquifers. For ATEs aquifer evaluation studies, porosity values should be obtained from a laboratory permeameter test of several representative samples.

When considered separately for given aquifer conditions, some very general guidelines for porosity can be established. Porosity values less than five percent are unsuitable and include most secondary porosities mentioned previously. Values for porosity between five percent and fifteen percent may be marginally acceptable and values greater than fifteen percent are most likely suitable for an ATEs aquifer. These porosity values must interact with other favorable aquifer characteristics to produce desirable results.

The flow velocity is also influenced by the hydraulic gradient, which is determined by the change in an aquifer's water level over a horizontal distance. Expressed in feet per foot or unitless, the hydraulic gradient is a measure of the driving force or energy responsible for the water movement in unconfined aquifers and plays a major role in confined aquifer flow systems. The hydraulic gradient is sometimes expressed as a percent; that is, the water level change (feet) per 100 feet of horizontal distance. Quantitative values for this characteristic are obtained by field measurements of the static water level in wells penetrating the aquifer. Because the hydraulic gradient has a complex interaction with other aquifer characteristics, a limiting guideline cannot be established for this characteristic. However, it is desirable for the overall flow velocity to be low (perhaps less than 50 ft/yr). If the ground-water velocity is excessive it will have to be taken into consideration when the well field is designed. The quantitative limits for hydraulic gradient must be determined by site-specific studies where its balance with other aquifer properties can be observed.

The last hydrodynamic parameter to be discussed is the storage coefficient (S). This is a dimensionless coefficient and can be interpreted as the amount of water in storage released from a column of aquifer with a unit cross section under a unit decline in head. Storage coefficient values are a measure of the pumping stress on an aquifer and are most often used to determine the effect of pumping stress on an aquifer's water level. This applies specifically to confined aquifers because the storage coefficient for confined aquifers is a function of the compressability of the aquifer's matrix and the changes in pore pressure.

Both of these conditions are insignificant under the water table conditions of an unconfined aquifer. Like the transmissivity values, the storage values are determined from analysis of pumping test data.

For the purpose of evaluating an aquifer's ATES potential, the storage coefficient's usefulness is questionable. Because confined aquifers generally have lower storage values, a comparison of the relative quantitative values can be helpful in determining if an aquifer is confined. Also, during the design of ATES facilities the storage coefficient may be used to assess the change in an existing hydraulic gradient caused by pumping during the recovery operation. Limiting guideline values for the storage coefficient were not determined.

Thermodynamic Properties

To evaluate a thermal energy storage system the thermodynamic properties of the system should be considered. These properties affect the shape of the stored energy mass and the distribution of the thermal energy in that shape. Both the shape and distribution of the thermal energy mass are important to the recovery economics of the system. A dual media system is involved with ATES because the thermal energy is stored in a saturated porous media. Heat transfer takes place within the solid and the liquid media of an aquifer. The majority of heat flow in the solid medium phase is by conduction and is largely controlled by thermal conductivity properties of the medium. The largest portion of heat flow in the liquid medium phase is by convection and fluid flow which is largely controlled by the hydraulic properties of the medium. The hydraulic properties have been discussed previously; the thermal properties of the solid medium are discussed next.

Conductive heat transfer is analogous to hydrodynamic flow. Therefore the media's thermal conductivity is analogous to transmissivity, and the heat capacity of the aquifer's matrix is analogous to an aquifer's storage coefficient. The thermal conductivity and the heat capacity are both properties of a medium, and vary with the medium's state. Thermal conductivity varies with temperature and the heat capacity varies with volume and pressure. Within the temperature ranges associated with ATES, the thermal conductivity change for a specific medium is negligible. The heat transfer process within an aquifer of an ATES system will proceed at a slow rate with a constant volume and pressure; therefore, heat capacity should also have a constant value for a particular aquifer matrix.

The thermal conductivity of the aquifer's matrix has the same role in heat transfer as it does in fluid flow. In the heat transfer process of an ATES system, the activity to be controlled is the heat transfer rate (Q) or the heat transfer rate per unit of area (q). The heat transfer rate is a function of thermal conductivity and temperature gradient, whose relationship is shown by the following equation:

$$q = K(T/L)$$

Where:

q = Heat Flux units of Btu/hr-ft²

k = thermal conductivity with units of Btu/hr-ft °F

T/L = temperature gradient; °F/ft

If heat energy is to be stored and recovered, it is desirable to have an extremely low heat transfer rate between the aquifer fluid and its matrix. This would allow the energy to move to the recovery point

by convection and fluid flow with minimal heat loss during the process. To accomplish this, either the temperature gradient or the thermal conductivity or both must be kept low. The temperature gradient is highly variable and depends upon the initial change in temperature between the aquifer water temperature and the injection fluid temperature and is controlled by the hydraulic flow properties. The temperature gradient will most likely be determined by site-specific studies. Therefore, the thermal conductivity value is a more useful parameter for evaluating an aquifer's potential for ATEs.

Thermal conductivity values can be expressed in engineering units Btu/feet-hour-degree fahrenheit; the ranges discussed here are expressed in the metric units as 10^{-3} calories/centimeter-second-degrees centigrade. The values discussed are for saturated earth materials. Unsaturated materials of similar composition will, in general, have values approximately one order of magnitude less because of containing air in the void space rather than the more conductive substance of water. For low temperature systems the lowest thermal conductivity values are desirable because of the marginal recovery economics of the low temperature or chill systems. The range in values is from 0.50 to 2.0 (10^{-3} calories/centimeter - sec. $^{\circ}\text{C}$) and includes saturated clay, silt and some types of coal. The thermal conductivity of water is in this range at 1.50. The lowest thermal conductivity range is desirable for small systems and chill storage but generally includes the low permeability unconsolidated materials such as clay and silt, which are undesirable. An acceptable range for thermal conductivity values is from 2.1 to 4.0 and includes most types of saturated sand and shale. The higher values are much less desirable and range from 4.1 to 8.0.

This range includes sandstone, slate, and limestone. Values higher than 8.0 begin to include the crystalline and silica-rich rocks that have undesirable properties other than their thermal conductivity. Therefore, the value of 8.0 is not an upper limit resulting entirely from undesirable thermal conductivity, but in general represents the upper limit of thermal conductivity for suitable permeable materials.

Because of the highly variable nature of earth materials the thermal conductivity value will most likely be determined from testing site-specific materials. The values presented above are for discussion purposes only and indicate guidelines showing the range of thermal conductivity values for some saturated earth materials commonly found as aquifers. The complex interaction of the aquifer's thermal properties with the hydraulic properties dictate the necessity of the interaction and balance for all aquifer properties. For this reason, it is likely that the thermal conductivity does not have a major role in aquifer evaluations but certainly should be acknowledged.

The thermal conductivity of both the aquifer matrix and the confining layers should be considered. This applies especially for low temperature and chill systems for which ideal thermal confinement is desirable because of the marginal economic recovery associated with low temperature and chill systems. For these systems an unsaturated confining layer, or in the unconfined case an unsaturated overburden, would be helpful owing to the lower thermal conductivity of unsaturated materials.

The second important thermodynamic property is the heat capacity of the aquifer matrix. This parameter relates the amount of internal energy change (as heat, enthalpy) to the temperature change of the

material. This parameter is analogous to the storage coefficient in hydraulic flow. As in the hydrodynamic case, the importance of this parameter in aquifer evaluations is questionable. However, it does give some indication of how much of the thermal energy may be stored in the aquifer matrix. Quantitative limiting guidelines for this parameter have not been established. This value should be kept at a reasonably low level so the stored energy will move from the injection point to the recovery point with minimal heat energy being stored in the aquifer matrix. As in the case of hydraulic flow, this value must be evaluated with respect to the thermal conductivity and other aquifer parameters.

Geochemical Properties

Data concerning the geochemical properties of aquifers are seldom found in the literature. The best data usually refer to the chemical quality of the water which in some cases reflects the chemical composition of the matrix and in other cases indicates the properties of the recharge water. Frequently, the chemical quality of the water is a product of the chemical interaction between the recharge water and the aquifer matrix. However, the chemical properties of the fluid, the matrix, and the confining layers are all important considerations.

A major concern is the chemical compatibility of the aquifer fluid with the injected fluid. If incompatible, the combination of certain chemicals derived from the aquifer fluid with the injected fluid can cause precipitates to form. This would result in clogging at the well bore and require higher injection pressures or backwashing of the well screen. In either case it would adversely affect the system operation and economy. A method of overcoming the potential incompatibility of fluids is to use the aquifer fluid for injection.

The chemical compatibility of the aquifer matrix and the injection fluid is also an important consideration. An incompatibility between these two can result in decreased permeability, decreased porosity or in other ways adversely affect the movement of water to the recovery point. This may be particularly true for high temperature systems because high temperature fluids have been known to cause a decrease in permeability. High temperature fluids may also cause a decrease in the confining layers' integrity through the increased solution capacity of the fluid, causing a breach to occur resulting in a loss of the injected fluid.

Because the geochemistry is unique to each site and can be dealt with through the design process, limiting guidelines will not be established. However, when available, chemical quality data of the aquifer water are provided in the computer table for each region and may be useful in future evaluations.

Qualitative Considerations

This section is intended to present a brief discussion of considerations other than those related to the ATES technology, but which have a bearing on the ATES potential of an aquifer. Since these items are more of a legal and/or aesthetic nature, they are not used to evaluate aquifers within the scope of this report. However, the site selection for an ATES production system will include these evaluations in the site-selection process.

The primary item of concern, and one for which data are easily obtainable, is that of present aquifer use. In many cases an aquifer has been committed, either legally or through past use, to domestic or

municipal water supplies. Aquifers in this category include those designated as sole source by the U. S. Environmental Protection Agency (EPA), and those included in municipal water system master plans. In these instances an aquifer's water supply is often being used to the limit of current development and has future allocations designated.

The second consideration is that of water rights and permits. The rapid increase in the geothermal field, primarily in the area of the ground-water geothermal heat pump, has resulted in many state and federal agencies adopting regulations restricting the application of this technology to particular aquifers and/or requiring permits for such facilities. At present, the geothermal field is concerned with domestic and commercial injection water in a temperature range from 10° C to 60° C. This range of temperatures often requires the use of surface heat exchanges and heat pumps for recovery efficiencies and is not included in the temperature range evaluations for aquifers of this study. By the time an operating ATES facility is to begin production there may be a considerable number of legal questions concerning the existing water rights of an aquifer and the permits for well injection.

The third consideration is very closely related to the first two, and concerns thermal pollution of an aquifer. This will certainly be a subject of the above-mentioned permit system and of the current use of an aquifer.

Region 1. Western Mountain Ranges

REGION 1 - WESTERN MOUNTAIN RANGES

INTRODUCTION

Region 1 consists of the continuous mountain ranges common to the western United States. The outline of this region is shown in Figure 1-1. Region 1 deals only with the mountain ranges and the few large intermontane valleys. A natural physiographic division of this region was easily made and is also shown in Figure 1-1. The six divisions of Region 1, herein referred to as provinces, follow the physiographic outline of various mountain ranges and are described as follows: 1) Sierra-Nevada; 2) Coast Range; 3) Cascade Range; 4) Northern Rocky Mountains; 5) Central Rocky Mountains; and 6) Southern Rocky Mountains. These six provinces are used throughout this chapter.

The region's climatological data vary markedly but have a general trend dictated by the orographic effect of the high ranges. The western slopes receive the greatest amount of precipitation, while the eastern slopes are in a rain shadow and receive considerably less annual precipitation. The annual precipitation for the western mountain ranges varies from a high of 80 to 90 inches for the Coast Ranges and Cascade peaks, to the Sierra-Nevada Range which averages from 50 to 80 inches annually (Oakeshott 1971). The rain shadow side of the two ranges varies from the desert conditions of the eastern Sierra-Nevada at 3 to 6 inches and from 7 to 16 inches for the east side of the Cascade Range (McKee 1972). The Rocky Mountain ranges receive from 50 to 75 inches annual precipitation in the mountain peaks, and approximately 5 to 15 inches for the eastern rain shadow side.

OUTLINE OF REGION I
SHOWING SIX MAJOR PROVINCES
FIGURE 1-1

The ground-water use varies little throughout Region 1. Owing to the abundance of high quality surface water, the ground-water resources have not been extensively developed. When readily available and of proper quality, groundwater is used for both domestic supplies and irrigation. Municipal ground-water supplies are not common to this region. Often, the high mountain watersheds are developed, via surface water reservoirs, for municipal and large irrigation supplies. Therefore, the ground-water resources of Region 1 have not had a major role in the region's development. A few exceptions to this are found in the larger intermontane valleys of the Rocky Mountains and are discussed in the following section.

GEOLOGIC FRAMEWORK

Region 1 is dominated by large mountain ranges which all have a general north to south trend. Smaller mountain ranges vary somewhat in their trend as does the local geologic structure. The western mountain ranges were created from two interrelated geologic activities. The first is the broad folding and overthrusting of the Rocky Mountain area. This type of structure results from large compressional forces associated with the movement of an oceanic plate against a continental plate. The second geologic activity responsible for the region's mountain ranges is the intrusion of large igneous rock bodies (plutons and batholiths) and volcanic activity. The theory of plate tectonics provides the background for these two geologic activities and is the mechanism that interrelates the mountain ranges' origins. A discussion of plate tectonics is beyond the scope of this report.

As stated in the introduction section of this chapter, the region may be divided into six provinces that correspond to the physiographic outline of various mountain ranges and are described as follows: 1) Sierra-Nevada; 2) Coast Range; 3) Cascade Range; 4) Northern Rocky Mountains; 5) Central Rocky Mountains; and 6) Southern Rocky Mountains. The following discussion outlines the general geologic framework of each of the six provinces.

SIERRA-NEVADA PROVINCE

The Sierra-Nevada province, as shown in Figure 1-1, is located in east central California and extends in a north-northwest direction for more than 400 miles. This province consists of the Sierra-Nevada Mountain Range, which can be generally described as a great block of granitic intrusive rock. The westward tilted rock has a gentle two degree slope on the west side; the east slope is marked by extensive faults and is one of the most abrupt slopes in the western mountain ranges. The Sierra-Nevada Mountain Range has its lowest elevations at the northern and southern ends where the peaks average from 6,000 feet to 7,000 feet above mean sea level. Mt. Whitney, the highest peak at 14,394 feet above mean sea level, is in the south central part of the range. Throughout the central mountain range many peaks exceed elevations of 12,000 feet above mean sea level. The southern end of the range turns westward at the end of the San Joaquin Valley and merges with the west trending Tehachapi Mountains which are not considered a part of this province. At the northern end, the geologic structures and rock formations of the Sierra-Nevada probably continue

beneath the Cascade Range and into the Klamath Mountains. Topographically, the Sierra-Nevada Range merges into the Cascade Range and the Modoc Plateau. The Klamath Mountains are considered a part of the Sierra-Nevada province whereas the Modoc Plateau is not (Figure 1-2).

The most significant geologic feature of the Sierra- Nevada Province is the massive granitic batholith of Mesozoic age which dominates the Sierra-Nevada Range. The Klamath Mountains also have granitic intrusions present; however, the principal rock types are marine sedimentary and volcanic rocks of Paleozoic and Mesozoic age (Oakeshott 1971).

The rocks exposed in both the Sierra-Nevada Range and the Klamath Mountains have been brought to the surface through tectonic processes that began during the Nevadan Orogeny of Mesozoic age. The geologic evidence suggests that the tectonism stopped during Early Tertiary time but was rejuvenated during the close of the Tertiary Period. The late Tertiary Period of tectonism produced coarse-grained sediments in the Sierra-Nevada foothills and resulted in the westward tilting of the Sierra-Nevada Range. Extreme faulting took place on the east side of the province and the faulting activity continued into the Quaternary Period (Oakeshott 1971).

The unconsolidated material overlying the bedrock is relatively thin throughout the Sierra-Nevada province. Even though continental ice masses did not reach this province, extensive alpine glaciation produced much of its present-day alpine form. Both alpine glacial material and Recent alluvium may be found in the major drainages of the province.

MAJOR GEOGRAPHIC AREAS
AS REFERENCED IN TEXT

COAST RANGE PROVINCE

The Coast Range province has a shorter and less well-known geologic background than the Sierra-Nevada province. This province, as shown in Figure 1-1, extends in a north-south direction from the southern Oregon border along the Oregon and Washington coasts to the Olympic Peninsula (Figure 1-2). The province is bordered on the west by the Pacific Ocean, on the east by the Puget-Willamette lowland, on the north by the Strait of Juan de Fuca, and on the south by the Klamath Mountains. The border with the Klamath Mountains is placed arbitrarily at the contact between Tertiary and pre-Tertiary strata (McKee 1972). The Coast Range is lowest in northern Oregon and southern Washington; a relationship seen also in the Cascade Range to the east. Separately named subdivisions of the Coast Range include the Willapa Hills in southwestern Washington and the Olympic Mountains to the north. The Olympic Mountains are the highest and the most rugged part of this province; peaks tower to an elevation of a mile or more above the surrounding lowlands.

The Coast Range is breached by only a few rivers. Most of the region is drained by short streams that flow west to the Pacific or east to the interior lowland. Throughgoing streams include the Chehalis River, which separates the Olympic Mountains from the Willapa Hills, the Columbia River, the Umpqua River and the Rogue River of southwest Oregon. None of these river channels provide a complete exposure of the bedrock in the Coast Range. The structure of the region has been pieced together primarily from small, isolated outcroppings found in road cuts, stream beds, and sea cliffs (McKee 1972).

The pre-Cenozoic geologic record for the Coast Range province is essentially non-existent. One theory for the absence of the geologic

record is that the area now occupied by the Coast Range was part of the oceanic plate called the Columbia Arc. A second theory states that pre-Cenozoic rocks are at great depths beneath the Coast Range province and were deposited in an area of great subsidence at the western edge of the Columbia embayment. Regardless of either theory, the Coast Range province contains rock formations deposited during the Cenozoic Era. The Coast Range was formed primarily during the Tertiary Period (McKee 1972; Mintz 1972).

The dominant rock type of the Coast Range province is a thick sequence of submarine basalts which are early Tertiary in age. The best exposure of these basalts is on the east flank of the Olympic Mountains where a total thickness of perhaps ten miles has accumulated. This is one of the thickest sections in the world; yet, owing to the difficulty in interpreting geology from such a vast homogeneous pile of lava, little is known about this formation. Subsequent metamorphism and extensive faulting have made stratigraphic study most difficult. These basaltic flows of early Tertiary age are known as the Crescent Formation, Metchosim Formation, Tillamook Volcanic Series, Siletz River Volcanics and Umpqua Formation (McKee 1972).

Post dating the submarine volcanic flows are extensive deposits of marine sediments. The earliest of these is the Tyee Formation in the southern Oregon Coast Range. This formation is composed of sediments derived from the bordering Klamath Mountains to the south and southwest. Throughout the Coast Range, marine stratigraphy is dominated by marine shales containing high proportions of volcanic ash. The Tertiary-aged sediments are markedly volcanic and contain a mixture of lava flows, volcanic mud flows, ash, conglomerates, sandstones and

siltstones rich in volcanic fragments. By mid-Tertiary time, orogenic activity began uplifting the Coast Range from the sea.

Post-Tertiary rocks are composed of shallow-water marine and non-marine sediments, siltstones and conglomerates that form the present-day terraces and coastal valley fill. Overlying these sedimentary units in the northern Olympic Peninsula are glacial deposits. Present-day drainages are filled with alluvium of Pleistocene and Recent age.

CASCADE RANGE PROVINCE

The Cascade Range (Figure 1-1) connects in the south with the Sierra-Nevada Range near Mt. Lassen and in the north merges with the Coast Range of British Columbia. The Cascades vary in width from a minimum of about 30 miles in southern Oregon to a maximum of about 80 miles in northern Washington. They have an average elevation of about 5,000 feet above mean sea level, but rise somewhat above this at each end. The most rugged topography in the Cascade Range province occurs in the North Cascades of Washington.

The Cascades are breached only by the Columbia and Klamath Rivers. Numerous rivers drain the west flank of the Range. The east side of the Cascade Range is drained by rivers that are tributary to the Columbia River, except for streams at the southern end of the range which flow out into the arid Basin and Range province. Thereafter, these streams generally disappear.

The Cascade Range contains very few rock formations originating prior to the Cenozoic Era. Formations of this age are found in the North Cascades and their western foothills (McKee 1972; Walker 1960). The oldest rocks are the highly metamorphosed schists and

gneisses in the North Cascade core. These rocks date back to the early Paleozoic Era.

The oldest rocks found throughout most of the Cascade Range are non-marine sediments and volcanic deposits of the early Tertiary Period. The sandstones, siltstones, and conglomerates of volcanic origin found in the Ohanapecosh Formation near Mt. Rainier are characteristic of these early Tertiary sedimentary deposits. Typical volcanic formations of this period are The Little Butte Volcanic Series in Oregon and the Keechelus Volcanic Group in Washington.

Granitic intrusions of Middle Tertiary age are common in the Southern and Central Cascades. The North Cascades Range have older granitic intrusions of Late Cretaceous age.

Tectonism and subsequent erosion, which began during the Late Tertiary Period, has removed much of the old Cascade Range and only small remnants of the old volcanoes remain. This erosional period is represented best by the sedimentary deposits rich in volcanic material. These formations are found in the eastern foothills and lowlands and are known as the Ellensburg Formation, the Dalles Formation, and the Deschutes Formation.

At the close of the Tertiary Period, volcanism began again and the Cascade Andesite Formation was extruded. Volcanic activity has been prominent throughout the Quaternary Period and produced the high, snow-capped strato volcanoes for which the Cascade Range is famous. The major drainages of the Cascade Range are filled with unconsolidated material of glacial and alluvial origin.

NORTHERN ROCKY MOUNTAIN PROVINCE

The Northern Rocky Mountain province (Figure 1-1) lies east of the Okanogan River, north of the Columbia Basin in north central Washington and extends eastward through the north Idaho Panhandle to the Continental Divide in western Montana (Figure 1-2). The region boundary follows the Continental Divide southward to Helena, Montana, eastward to include the Belt Mountains and Little Belt Mountains of Montana, then south towards Bozeman, Montana, and southeast along the Absaroka Range and Beartooth Plateau to the Montana-Wyoming state line. At this point, the boundary line follows a somewhat arbitrary route southwest to the Continental Divide at the Wyoming-Idaho-Montana borders and continues west and northwest to north central Idaho and northeast Washington. Figure 1-1 shows the outline of this province.

The dominant rock type of the Northern Rocky Mountain Province is shallow-marine sedimentary rocks deposited periodically along the western margin of the North American Continent from Precambrian through Mesozoic time. These sedimentary units consist of sandstones, limestone and shale.

In the northern part of the province, a thick succession of shallow water marine sedimentary rocks of Precambrian age are exposed. The well-stratified beds of limestone, shale, and quartz sandstone have a total thickness of approximately 50,000 feet and are exposed throughout northeast Washington, north Idaho, and western Montana (McKee 1972; Mintz 1972). These units are known collectively as the Belt Super Group and have their best exposure in Glacier National Park where they have been thrust over younger Paleozoic strata along the Lewis Thrust Fault.

The Early Paleozoic sedimentary rocks are difficult to distinguish from the Precambrian Belt Super Group owing to a continuation of a similar depositional environment. This is particularly true in northeast Washington where approximately 15,000 feet of Cambrian marine strata are found in the Okanogan Highland (McKee 1972). The shallow water marine environment continued for several hundred million years, as shales and shallow-water limestones were deposited throughout the Ordovician, Silurian and Devonian Periods. Western Montana has marine deposits of Cambrian age (Flathead Sandstone, Wolsy Shale, and Meagher Limestone), but is essentially void of Ordovician, Silurian, and early Devonian aged strata (Perry 1962). Deposits of the mid-Devonian Period, the Three Forks Shale and Jefferson Limestone Formations, are found in western Montana. The marine deposits of the Mississippian System are absent throughout all but the southeast part of this province where the Madison Limestone occurs.

The Mesozoic Era began with a continuation of marine strata deposition. Near the end of the Jurassic Period, there was a change from a marine to a continental depositional environment as evidenced by a continental shale and sandstone deposit, the Morrison Formation. Continental deposition continued with the Kootenai Formation. This rock formation contains conglomerate and sandstone, indicating a highland to the west. The rising western highland in the Early Cretaceous Period marks the beginning of a major mountain building period known as the Laramide Orogeny. Large granitic intrusions in central Idaho and the Okanogan Highlands were emplaced at this time. The Laramide Orogeny continued into the early Tertiary Period resulting

in uplifting and subsequent erosion. Coarse-grained continental sediments were deposited in the intermontane basins adjacent to the rising highlands.

Valley-fill lakes were formed in western Montana during the late Tertiary Period. These lakes often received much volcanic ash, probably from volcanic activity to the west. Deposits from late Tertiary lakes are found in the Flathead, Missoula and Bitterroot valleys of northwestern Montana (Perry 1962; McMurtrey, Konizeski and Brietkrietz 1965). In the Okanogan Highland area, the erosional valleys were filled with the basalts from the Columbia River Group; subsequent uplifting and erosion removed much of these basalts from this province.

The northern half of this province was covered by vast lobes of the Cordilleran Ice Sheet during the Pleistocene Epoch. Several advances and retreats of this ice sheet resulted in a variety of glacial deposits throughout the northern part of the province. The final stages of retreat of the ice lobe, which extended down the Purcell Trench into northern Idaho, blocked the flow of melt water from the eastern glaciers and formed ancient Lake Missoula. This lake formed within the Missoula Basin, Bitterroot Valley, and extended into the Blackfoot Valley, 25 miles east of Missoula (McMurtrey, Konizeski and Brietkrietz 1965). Extensive Quaternary lacustrine and alluvial sediments were deposited at elevations to 4,200 feet above mean sea level and were often up to 400 feet thick. A subsequent breaching of the ice dam in Northern Idaho drained the lake rapidly and left extensive gravel and boulder deposits in the northern Idaho Panhandle area. The highland slopes throughout the province were eroded extensively by alpine glaciation during the Pleistocene Epoch.

MIDDLE ROCKY MOUNTAIN PROVINCE

The Middle Rocky Mountain province, as shown in Figure 1-1, is located in Wyoming, northeastern Utah and eastern Idaho. The Laramie Range on the east and Wasatch Range on the west form the two north-south trending arms of this province, which is separated by the Green River Basin in south central Wyoming. Topographically, this province has primarily north to south trending mountain ranges and broad intermontane valleys. The main structural element in these mountain ranges is a series of nearly horizontal thrust faults along which the upper blocks have moved eastward.

Rock formations of Precambrian age are not of major significance in this province. When exposed, these rock types are generally igneous intrusive rocks and some metamorphosed sediments. The Precambrian aged Beartooth-Big Horn structural province located near the Montana-Wyoming border has igneous intrusions that are some of the oldest rocks found in the United States.

The Paleozoic Era was a time of great marine sedimentation throughout the west central area of the United States. In particular, the Rocky Mountain area received thick deposits of Paleozoic marine sediments. In this province, the rock formations are known as the Flathead Sandstone, the Gros Ventre Formation, and the Gallatin Formation (Lowry, Lowham and Lines 1976). The Big Horn Dolomite of Ordovician age is also found throughout this province. The Devonian System contains shales and siltstones of the Jefferson and Three Forks Formation. The Mississippian System is dominated by the Madison Limestone which is overlain by the Amsden Formation consisting of shale and limestone (Perry 1962). During Pennsylvanian time a significant change

in deposition occurred. During this time, a very extensive formation of well-sorted clean sand was deposited. This is a near shore deposit and in some localities resembles dune sand. Known as the Tensleep Sandstone in Wyoming, it is equivalent to the Quadrant Sandstone in Montana, the Casper Formation to the east, and the Webber Quartzite to the south (Hood 1976; and Perry 1962). The close of the Paleozoic Era was marked by deposition of siltstone, limestone, and dolomite.

During the earliest part of the Mesozoic Era, marine sediments were deposited. The Dinwoody Formation, consisting of siltstones interbedded with shale and gypsum, was deposited along the western side of the province. Parts of the Phosphoria Formation (Permian and Triassic Periods) are found in the western side of the province. Deposition during the late Triassic Period was mainly non-marine, resulting in extensive continental deposits known as the terrestrial redbeds. The largest portion of such deposits are east and north of this province. These deposits are represented in northwestern and north central Wyoming by the Chugwater Formation, the Ellis Group, and the Nugget Sandstone (Lowry, Lowham and Lines 1976).

The close of the Jurassic Period and the beginning of the Cretaceous Period was a time of continental deposition. The Cloverly, Morrison and part of the Kootenai Formation were deposited in the mid-Rocky Mountain province at this time (Mintz 1972; and Whitcomb and Lowry 1968). These deposits are predominantly fine-grained siltstones, mudstones with freshwater limestones, and some channel sandstone deposits. During the early and the Middle Cretaceous Period the depositional environment changed from continental to marine. Cretaceous-aged marine sediments include the Thermopolis Shale, Mowry Shale, the Frontier

Formation (fine-grained sandstone), the Cody Shale, and the Mancos Shale (Hood 1976; Lowry, Lowham and Lines 1976).

During the Cretaceous Period, the Laramide Orogeny began and the subsequent uplifting marked the end of the marine deposition for this province and most of the Rocky Mountain area. The initial deposits were quite extensive and consisted of sandstones and shales with minor deposits of coal as swampy areas were infilled. Typical formations include the Mesaverde Formation, Meeteetse Formation, Lance Formation and the Carrant Creek Formation in northeast Utah (Hood 1976).

The Laramide Orogeny occurred primarily during the Tertiary Period of the Cenozoic Era. The beginning of this era was marked by much overthrusting of the Paleozoic and Mesozoic-aged rock formations. Large structural basins were formed during this period of deformation. The basins, such as the Big Horn Basin and the Wind River Basin of Wyoming, are generally bounded on at least two sides by the uplifting mountain ranges. The resulting erosion provided a tremendous thickness of sediments (10,000 feet to 15,000 feet) that were deposited during the Tertiary Period (Lowry, Lowham and Lines 1976). Typical formations are the Fort Union, Willwood, Tatman, Wind River, Pinyon Conglomerate, Hoback, and Pass Peak Formations in Wyoming, and the Wasatch, Green River, Uinta and Duchesne Formations of northeastern Utah (Hood 1976).

Rocks deposited during the late Tertiary Period also contain much volcanic-derived sediment and other volcanic rocks. The origin of the volcanic material is primarily southwestern Montana and the Yellowstone National Park area. Volcanic rock and volcanic sediments were derived from the andesitic flows in the Absaroka Range and various extrusive

volcanic rocks in Yellowstone National Park, northeastern Utah and southwestern Montana (Cox 1976). The Wiggins Formation and the White River Formation contain much volcanic-derived sedimentary rock and are widespread throughout the western side of the province.

The Arikaree Formation and Moonstone Formation are the dominant late Tertiary-aged continental sediments in the Wind River Basin (Whitcomb and Lowry 1968). To the northwest, near Yellowstone National Park, Jackson, and southeastern Idaho, the Colter, Camp Davis, Teewinot and Bivouac Formations are dominant (Cox 1976). These formations of the northwestern part of the province are especially thick, up to 7,000 feet in thickness, and contain appreciable amounts of volcanic rock.

The Quarternary Period of the Cenozoic Era began with accumulation of extensive gravel terrace deposits in north central Wyoming. Alpine glaciation was extensive in the newly uplifted ranges and extended south into the Yellowstone National Park area from the Absaroka and Beartooth Mountains in Montana.

SOUTHERN ROCKY MOUNTAIN PROVINCE

The Southern Rocky Mountain province is contained within west central Colorado and a very small part of north central New Mexico. As shown on Figure 1-1, the eastern border follows the Colorado Front Range south to the Sangre de Cristo Range in north central New Mexico and includes the San Juan Mountains on the southwest border. The western border is formed by the east side of the Colorado Plateau. Topographic relief is great; the mountainous area of the east reaches

1972). The Mesa Verde Group contains a massive, fine-grained sandstone, carbonaceous shale, sandy shale, and coal. Other formations derived from the Laramide Orogeny include the Sawatch Formation and the Fort Union Formation. The Sawatch Formation consists of claystone, mudstone, and shale with siltstone and conglomerate interbeds. The Fort Union Formation contains interbedded sandstone, shale, and lignitic coal.

Deposits of late Tertiary age contain volcanic rock and volcanic-derived sediment. Some intrusions of granitic rock also took place. The Browns Park Formation in northwestern Colorado contains some amounts of volcanic ash interbedded with the sandstones (Brogden and Giles 1977). The majority of volcanic rocks were unnamed in the available literature.

Deposits of Quaternary age include some basalt lava flows in northwestern and west central Colorado. The main activity during the Quaternary Period was stream erosion. This activity actually started in the late Tertiary Period and is evident today by the deep canyons such as the Royal Gorge of the Arkansas River which cuts the Colorado Front Range, and the Black Canyon of the Gunnison River.

heights up to 14,000 feet above mean sea level and is cut by superimposed rivers such as the Arkansas River in the Royal Gorge of the Colorado Front Range.

Very little is known about the Precambrian strata in this province. The available literature described very limited exposures of gneiss and schists with some granite. The most studied rock formations are of middle Paleozoic age. As is common throughout the Rocky Mountain area, marine sediments of Paleozoic age were deposited in this province. These early formations are named as follows: Peerless Formation, Maitou Dolomite, and Chaffee Formation. The Leadville Limestone of the Mississippian age is a part of the Paleozoic sedimentary sequence and consists of varying strata of limestone, dolomite, sandstone and chert. The rock formations deposited during the Pennsylvanian and Permian Periods consist of fine-grained sandstone, siltstone, shale, gypsum, and conglomerate with volcanic material. These deposits include the Eagle Valley Evaporite, Maroon Formation and Webber Sandstone.

The Middle Rocky Mountain Province contains a thick sequence of continental sediments deposited during Mesozoic time. Continental sandstones and siltstones of Triassic and early Jurassic age include the following: State Bridge Formation; Chinle Formation; Entrada Sandstone; Sundance Formation; and in northern Colorado, the Chugwater Formation.

The Laramide Orogeny, which occurred during the Late Cretaceous and early Tertiary Periods, produced large quantities of sediment. Some of the sedimentary deposits are associated with the Mesa Verde Group common to much of the Southern Rocky Mountain region (Boettcher

HYDROGEOLOGIC FRAMEWORK

In the following section, the hydrogeology of Region 1 is discussed as it pertains to the major water-yielding rock formations of each province. Region 1 is defined to include only the western mountain ranges. As discussed in the Geologic Framework section, the Sierra-Nevada province, Cascade Range province, and the Coast Range province are predominantly steep, young mountain ranges without extensive valleys, plateaus or other lowlands. Owing to these factors, these three provinces do not contain extensive water-yielding strata or regional aquifers. The ground-water supplies developed in these provinces are obtained predominantly from local alluvial sources and some younger, fractured lava flows. Most aquifers of this type are developed on a local scale and the available literature has very few specific data pertaining to them. Owing to the regional scope of this study, a discussion of the hydrogeologic framework for the Sierra-Nevada, Cascade Range, and Coast Range provinces is not included in this report. Instead, the discussion begins with the Northern Rocky Mountain province.

NORTHERN ROCKY MOUNTAIN PROVINCE

For the purpose of this discussion, the hydrogeologic framework of the remaining three provinces consists of six separate hydrogeologic environments. The hydrogeologic environments are separated by geologic age of the rock formations and by their lithology. The six hydrogeologic environments are as follows: 1) Quaternary deposits; 2) Tertiary volcanics; 3) Laramide Clastics; 4) Cretaceous marine sediments; 5) Lower Mesozoic sediments; 6) Paleozoic sediments. Not all

provinces contain water-bearing strata for each environment, but in general this type of breakdown works well.

Quaternary Deposits

In the Northern Rocky Mountain province rock deposits of the Quaternary System are chiefly glacial till, glacial outwash, river alluvium, and lacustrine deposits. The groundwater in these deposits is often in hydrologic connection with surface water systems and, therefore, receives abundant recharge. Precipitation, the other recharge source, is also significant. The majority of this province receives at least 20 inches of precipitation annually. The discharge is most often to surface water and sometimes to the underlying strata. The aquifers associated with Quaternary deposits are unconfined and have highly variable yields. The variable yields are a result of the glacial outwash sands and gravels interfingering with the fine-grained lacustrine and till deposits. The largest and most predictable aquifer in glacial deposits is the Rathdrum Prairie Aquifer in northern Idaho and eastern Washington. Other large, valley-fill, glacial deposits are in the Missoula Basin area and generally have much smaller yields and are not uniformly extensive (Boettcher and Gosling 1977). Owing to the presence of glacial lacustrine deposits interfingering with the sands and gravels, the deposits in the Missoula Basin generally have lower yields than the Rathdrum Prairie Aquifer.

Tertiary Volcanics

Within the Northern Rocky Mountain province, volcanic deposits of Tertiary age are primarily limited to northeast Washington and southwest

Montana. The volcanic activity in southwest Montana was of a limited and very local nature during Tertiary time. The basaltic lavas of late Tertiary time are generally above the local ground-water level and may have been eroded to remain as isolated remnants. In northeast Washington, the Tertiary volcanics are part of the Columbia River Basalt Group. The lava flows in this province are at the very margins of the Columbia Plateau, yield water through fracture porosity and are only small ground-water reservoirs owing to topographic terminations.

Laramide Clastics

The Laramide Clastics of the Northern Rocky Mountain province include the extensive lakebeds in the Missoula Basin and Flathead Valley areas of Montana. Ground-water yields from the lacustrine deposits in these valleys are small. However, in other valleys which do not contain Tertiary lake sediments, the sedimentary deposits are coarse-grained and are frequently developed for agricultural, domestic, and some industrial use (Boettcher and Gosling 1977). Recharge by precipitation and discharge to stream flow is minimal. In some areas, these saturated deposits recharge the underlying rock formations.

Cretaceous Marine Sediments

The marine sediments of the Cretaceous System of the Northern Rocky Mountain province are primarily shales, siltstones, and well-cemented sandstone conglomerates. Throughout this province, these rock formations yield little water. In the intermontane basins, the Cretaceous marine sediments are often much deeper than the overlying, more permeable sediments and are therefore seldom developed for their

ground-water resources. They are important to the hydrogeologic system because where the formations are exposed at the basin margins the fracture systems frequently discharge large volumes of water to the local stream flow.

Early Mesozoic Sediments

Within the Northern Rocky Mountain province, the early Mesozoic sediments are characterized by the continental sandstone and gypsum of the Chugwater Formation. This rock formation is at excessive depths throughout most of the province, or when near the surface is often too fine-grained to yield substantial amounts of water. Exceptions are near outcrop areas where extensive fracturing has resulted in large secondary porosity. In general, the development of groundwater from the early Mesozoic sediments occurs primarily on a local basis.

Paleozoic Sediments

Paleozoic rock formations of the Northern Rocky Mountain province are chiefly marine deposits of limestone, dolomite, shales, and siltstones. In the southwestern part of Montana, the Flathead Sandstone of Cambrian age and the Quadrant Quartzite of Pennsylvanian age are two formations that most often yield water to wells. These formations most often yield to flowing artesian wells with large surface flows of 200 gallons per minute to 1,100 gallons per minute (Lowry, Lowham and Lines 1976). These two formations often yield water as a result of the primary porosity associated with well-sorted sandstones. Higher yields are

often available where these formations have been subjected to deformation and have secondary porosity associated with fracturing. The Madison Limestone (Mississippian age) is also present in southwestern Montana and contains abundant groundwater. The Madison Limestone depends primarily upon secondary porosity for well yields. Owing to this, large yields (700 gallons per minute) can be obtained from small vertical intervals with only a small loss in head, or the yield can vary to less than 200 gallons per minute with a large loss in the hydraulic head. This hydraulic head variation is typical of limestone deposits with secondary porosity associated with solution cavities and fractures. The Madison Limestone is an artesian aquifer and groundwater generally flows at the surface from wells finished in this formation (Lowry, Lowham and Lines 1976; Whitcomb and Lowry 1968; and McGreevy, Hodson and Rucker, 1969).

MIDDLE ROCKY MOUNTAIN PROVINCE

Hydrogeologic data for the Middle Rocky Mountain province are chiefly from the large intermontane valleys such as the Big Horn Basin and the Wind River Basin. Although most of the ground-water supplies are obtained from near surface deposits of alluvium and sediments, hydrogeologic data for the deeper rock formations is available from oil well data.

Quaternary Deposits

The Quaternary-aged terrace deposits along the major rivers of the Middle Rocky Mountain province are frequently developed for stock and domestic water use. Glacial deposits and alluvium within the basins are

frequently too fine-grained to have significant well yields (four gallons per minute to six gallons per minute). The alluvium from mountainous areas is often coarser-grained and has higher well yields. However, yields are generally limited (50 gallons per minute to 100 gallons per minute) by the small saturated thickness of the deposits (Robinove and Langford 1963). The thickest, and highest yielding, deposits occur in the Greybull River Valley where water supplies developed from the Sunshine and Greybull Terrace are often withdrawn at rates from 500 gallons per minute to 1,000 gallons per minute. The recharge to such terraces is often from precipitation, irrigation, and leakage from canals and other small streams.

Tertiary Volcanics

The water-bearing properties of these deposits vary dramatically owing to the variety of lithologies and depositional environments. Generally, the Tertiary-aged volcanic rock formations are not considered major aquifers. Local development is possible where the older flows have been fractured and where the clastic volcanic deposits lie below the local ground-water table.

Laramide Clastics

As is common in the other Rocky Mountain provinces, the Laramide clastics in the Northern Rocky Mountain province have been the primary formations developed for groundwater. The best water-yielding strata are the sandstones interbedded with the other fine-grained sedimentary deposits. However, the depth to the sandstone layer with a saturated thickness capable of large well yields (100 gallons per minute to 500

gallons per minute) varies tremendously with location. The water-yielding strata are discontinuous and sometimes are non-existent below a 300 foot depth (Whitcomb and Lowry 1968). Typical water-yielding formations are as follows: Wind River Formation; Duchesne and Uinta Formations; Arikaree Formation; Willwood and Fort Union Formations. These formations commonly have individual thicknesses from 2,000 to 5,000 feet thick. The water-yielding strata associated with these formations are discontinuous channel sandstones, which are most commonly found in the southwest portion of the Big Horn Basin and the west side of the Wind River Basin (McGreevy, Hodson and Rucker 1969). Because these clastic deposits were deposited contemporaneously with the Laramide deformation, the secondary permeability (fractures and joints) will be less than in the older rock types. Aquifers in these formations have been developed extensively in this province and are discussed further in this chapter as aquifers with an ATEs potential.

Cretaceous Marine Sediments

Throughout the three Rocky Mountain provinces, the Cretaceous marine sediments are seldom major aquifers. Formations in the Middle Rocky Mountain province generally include the following: Thermopolis Shale; Mowry Shale; Frontier Formation; Cody Shale; and Mancos Shale. The sandstone of the Frontier Formation and the sandstone interbeds of the Thermopolis Shale yield small amounts of groundwater to wells. Typical well yields are consistently below 50 gallons per minute throughout the province. The very limited well yields are often the result of the fine-grained nature of these sediments and the relatively small thickness of the sandstone interbeds which often average only 30 feet (Lowry, Lowham and Lines 1976; Whitcomb and Lowry 1968).

Early Mesozoic Sediments

Early Mesozoic sediments of the Middle Rocky Mountain province contain sandstone formations that have been subjected to deformation. The well yields for most sandstone formations are generally below 50 gallons per minute. The exception to this is where these formations have been subjected to extensive deformation, producing fracture zones which substantially increase the well yields. The formation that most frequently bears water is the Cloverly Formation, which can yield up to 350 gallons per minute when properly developed (Whitcomb and Lowry 1968).

Paleozoic Sediments

Rock formations of this hydrogeologic environment in the Middle Rocky Mountain province are generally highly fractured and steeply dipping. Throughout most of the province they are found at great depths. The Pennsylvanian-aged Tensleep Sandstone is the major aquifer of Paleozoic age in this province. The large well yields from this formation are chiefly the result of the primary porosity of the well-sorted sandstone. The Tensleep Sandstone is frequently an artesian aquifer with large surface flows. In the deformed areas of this formation, higher well yields are possible owing to the secondary porosity. Throughout most of the large basins such as the Big Horn Basin, the altitude of this formation is 6,000 to 7,000 feet below sea level. This is approximately equal to a depth of 10,000 to 12,000 feet below land surface. Along the basin margins, the Tensleep Sandstone is at shallower depths and lies within 1,000 feet of land surface. The majority of wells tapping this aquifer are located in these areas. The

middle Cambrian aged Flathead Sandstone is a similar formation, but occurs at even greater depths. These two formations often have individual flowing yields of 200 gallons per minute to 1,100 gallons per minute (Whitcomb and Lowry 1968).

The greatest development of aquifers with secondary porosity occurs in the Paleozoic formations, particularly the Big Horn Dolomite and the Madison Limestone, which can obtain water from large solution cavities. The well yields from these formations often vary from 200 gallons per minute to over 2,000 gallons per minute. Most water-bearing zones occur at great depths and frequently saline water is a problem associated with these zones. The best wells are developed close to the outcrop areas in the mountainous foothills areas (Whitcomb and Lowry 1968; McGreevy, Hodson and Rucker 1969).

SOUTHERN ROCKY MOUNTAIN PROVINCE

The hydrogeologic environments of the Southern Rocky Mountain province are generally the same as those previously discussed. The primary difference is that the province contains significantly more continental deposits and the older marine limestones, dolomites, and shales are generally not exposed. Throughout this province, the ground-water resources are scarce. Extensive rock formations with moderate to large ground-water yields are not present. The fine-grained sandstone, shales, and other continental deposits in this province generally yield less than 30 gallons per minute (Brogden and Giles 1976; Boettcher 1972). Locally, wells tapping Quaternary alluvium have higher yields. However, since glaciation was not a dominant factor in this province, the Quaternary deposits are not extensive and

are often confined to river channels. Owing to the very low well yields and general lack of detailed aquifer data on the water-yielding strata of this province, a discussion of each hydrogeologic environment is not included in this report.

MAJOR AQUIFERS

The previous sections of this chapter described the basic geologic framework and hydrogeologic framework for Region 1, identifying and briefly describing its major aquifers. Table 1-1 provides a listing of the major aquifers in the region. For the purpose of this study, a major aquifer is identified as an aquifer with significant areal extent that can sustain typical well yields of at least 50 gallons per minute throughout its areal extent.

Major aquifers for Region 1 (Table 1-1) are listed by the six hydrogeologic environments previously discussed. It was necessary to do this because listing the individual water-yielding rock formations within each hydrogeologic environment would be excessively long. Also, owing to the change in stratigraphic nomenclature between each province, a separate listing by formation name would become repetitious and confusing.

The most significant water-yielding strata within each province and for each hydrogeologic environment were briefly described in the preceding hydrogeologic framework section. The listing of aquifer data presented in Table 1-2 pertains to those specific rock formations previously discussed, but the data have been collected, tabulated, and presented under the general hydrogeologic environment divisions for the sake of clarity and simplicity. Qualitative geologic characteristics of each hydrogeologic environment are generalized and presented in Table 1-2. The specific reference for which data is cited can be identified by checking the title of the numbered reference given after each set of data.

AQUIFERS UNSUITABLE FOR ATES

All of the major aquifers of Region 1 have been evaluated according to the guidelines established in the Introduction. On this basis, many of the aquifers have been judged as generally unsuitable for ATES. In most cases, site-specific studies are needed to more fully evaluate the ATES potential of each aquifer. The aquifers judged unsuitable at this time for ATES are discussed below, together with the justification for their elimination. The aquifers are discussed according to the format established in the hydrogeologic framework section of this chapter as follows: 1) Quaternary deposits; 2) Tertiary volcanics; 3) Laramide clastics; 4) Cretaceous marine sediments; 5) Early Mesozoic sediments; and 6) Paleozoic sediments. Figure 1-3 provides a listing of the major aquifers in Region 1 considered unsuitable for ATES at this time.

QUATERNARY DEPOSITS

Sand and gravel aquifers deposited throughout the Quaternary Period are capable of sustaining the minimum well yield (50 gallons per minute) throughout the region. In many localities, particularly the local river alluvial deposits, well yields on the order of 1,000 gallons per minute are obtainable. However, the sedimentary depositional environment associated with rivers and streams results in rapid facies changes. Because of these rapid facies changes, the sand and gravel aquifers are generally not widespread, and hydrogeologic conditions may change markedly over the extent of the aquifer. In many instances, an alluvial aquifer may be confined in one locality and unconfined in others.

AQUIFER	REASONS FOR UNSUITABLE RECOMMENDATIONS	COMMENTS
Quaternary Deposits - Alluvium - Outwash	Rapid facies changes make the hydrologic conditions vary place to place; therefore aquifers are sub-regional in extent.	Site-specific studies may provide information that proves these aquifers are suitable for A.T.E.S. at a particular location.
Tertiary Volcanics	Fracture Porosity	All aquifers with fracture porosities are considered unsuitable for A.T.E.S. at this time owing to the random and unpredictable volumes of stored water in these aquifers.
Laramide Clastics - Northern Rocky Mountain Province	Rapid facies changes make the hydrologic conditions vary place to place; therefore aquifers are sub-regional in extent.	Site-specific studies may provide information that proves these aquifers are suitable for A.T.E.S. at a particular location.
Cretaceous Marine Sediments	Fracture Porosity	All aquifers with fracture porosities are considered unsuitable for A.T.E.S. at this time owing to the random and unpredictable volumes of stored water in these aquifers.
Early Mesozoic Sediments	Fracture Porosity	All aquifers with fracture porosities are considered unsuitable for A.T.E.S. at this time owing to the random and unpredictable volumes of stored water in these aquifers.
Paleozoic Sediments	Excessive depth and fracture porosity.	All aquifers with fracture porosities are considered unsuitable for A.T.E.S. at this time owing to the random and unpredictable volumes of stored water in these aquifers.

MAJOR AQUIFERS UNSUITABLE FOR A.T.E.S. IN REGION I

FIGURE 1-3

Site-specific studies may establish that alluvial sand and gravel aquifers at a particular location may be suitable for ATES. However, in the majority of localities, the aquifers associated with alluvial deposits have highly variable yields, are closely associated with surface water levels, and in general are not of a regional extent. The regional scope of this study thus eliminates these sub-regional alluvial aquifers from further consideration.

Many sand and gravel aquifers are associated with glacial outwash deposits and some of these aquifers are much larger in extent than the river alluvial deposits. This is particularly true for the Rathdrum Prairie Aquifer in north Idaho and eastern Washington and for some glacial deposits in the Missoula and Flathead Valley area of northwestern Montana. The glacial deposits of northwestern Montana are considered unsuitable for ATES development primarily because of the highly variable nature of these water-bearing strata. The permeable sand and gravels interfinger with less permeable lacustrine and glacial till deposits. Site-specific studies for these aquifers will be necessary to actually determine their ATES potential.

For the Rathdrum Prairie Aquifer, the areal extent approaches that which is acceptable for regional consideration, however, other hydrogeologic parameters limit the aquifer's potential for ATES. The highly permeable sand and gravel deposits of this aquifer result in excessive velocities unsuitable for ATES facilities (Hammond 1974; Drost and Seitz 1978). However, as is common in the outwash deposits, selected areas of this aquifer may contain less permeable strata, which are more suitable for ATES facilities. Again, site-specific data will be necessary to determine the usefulness of this aquifer for ATES.

TERTIARY VOLCANICS

For the three Rocky Mountain provinces, Tertiary volcanic rock deposits do not represent major or regional aquifers. This hydrogeologic environment is discussed and listed primarily because Tertiary volcanic rocks are widespread throughout the region and the water-bearing strata are often developed locally within the various regional provinces. In some areas, wells yield more than 100 gallons per minute. However, the aquifers in Tertiary volcanic rock have their highest yields owing to secondary porosity associated with fracture zones. Secondary porosity aquifers are excluded from ATEs consideration for reasons discussed in the Introduction. In areas where secondary porosities have not been developed, the fine-grained nature of the deposits generally results in yields below the minimum 50 gallons per minute. These deposits generally appear unsatisfactory for ATEs.

LARAMIDE CLASTICS

The relatively undeformed sediments deposited as a result of erosion of the uplifted areas during the Laramide Orogeny occur throughout the Tertiary System. The major aquifers in these rock formations occur in the Northern Rocky Mountain province and the Middle Rocky Mountain province. The Northern Rocky Mountain Laramide clastics generally were deposited in the late Tertiary Period, but the Laramide clastics of the Middle Rocky Mountain province were laid down in early and mid-Tertiary time. The two types of deposition are significantly different and have major hydrogeologic differences when considered for ATEs.

Laramide clastics deposited in the Middle Rocky Mountain province are generally continental sandstones interbedded with shale and siltstones. These deposits are much thicker than the Northern Rocky Mountain Laramide clastics. Some formations have a total thickness of 8,000 feet. Individual permeable layers of sandstone commonly have a thickness from 50 to 150 feet. Middle Rocky Mountain Laramide clastic deposits may have ATEs potential and, therefore, are discussed in a following section.

The Northern Rocky Mountain sediments deposited during the Laramide Orogeny commonly occur in lacustrine environments. The ancient lake beds in the Missoula, Flathead, and Deer Lodge Valleys are examples. The lacustrine Tertiary deposits contain some sandstone layers with sufficient permeability to be considered major aquifers. The total thickness of the Tertiary lacustrine deposits are approximately 5,000 feet in the Deer Lodge Valley, and 3,000 feet in the Missoula Valley (Boettcher and Gosling 1977). These deposits generally consist of poorly bedded sandstone, siltstone, conglomerate, shale, coal, and volcanic ash (Boettcher and Gosling 1977). The hydrogeologic data are generally restricted to the upper 500 feet. These deposits exhibit highly variable yields. The yield variability (10 to 1,000 gallons per minute) relates to the poorly bedded nature of these deposits and to the intermixing with fine-grained lacustrine sediments. The Laramide clastic deposits of the Northern Rocky Mountain province are considered unsuitable for ATEs owing to the above-mentioned discontinuity of permeable strata, and variable aquifer characteristics. Site-specific studies are necessary to identify locations where the aquifers in the

Tertiary-aged sediments of the Northern Rocky Mountain province may have conditions suitable for ATEs.

CRETACEOUS MARINE SEDIMENTS

Throughout Region 1, the marine sedimentary deposits of the Cretaceous System are extremely poor aquifers. Specific aquifer data were not available for the limited water-yielding strata in this hydrogeologic environment. Maximum well yields seldom exceed 50 gallons per minute. Most Cretaceous sediments are found deep beneath the overlying Cenozoic-aged strata. The highest yields of the aquifers are always associated with secondary porosity and water is generally saline at depth. The Cretaceous marine sediments are considered unsuitable for ATEs, primarily on the basis of insufficient yield and the occurrence of secondary porosity.

EARLY MESOZOIC SEDIMENTS

The Early Mesozoic sedimentary deposits of Region 1 contain more sandstone than the other Mesozoic sediments. However, these deposits are often fine-grained sandstone and siltstone continental deposits that are well cemented and have little primary porosity. Well yields vary with location, but are generally low (10 to 80 gallons per minute). The formation with the highest water yield (350 gallons per minute) is the highly fractured Cloverly Formation (Whitcomb and Lowry 1968). Other shales and sandstone interbeds may also have yields approaching this range, but they were not cited in the available literature. Generally, yields above 50 gallons per minute are associated with the secondary

porosity of fractures, holes, and faults. These sediments were subjected to deformation during the Laramide Orogeny and therefore have extensive fracture systems that are responsible for the higher well yields. The Early Mesozoic sediments are considered unsuitable for ATEs on the basis of secondary porosity and overall low well yields.

PALEOZOIC SEDIMENTS

As discussed in the preceding Hydrogeologic Framework section, several Paleozoic formations yield large volumes of water commonly flowing to artesian wells. Aquifers in this hydrogeologic environment are either sandstone (Paleozoic clastics) or limestones (Paleozoic carbonate deposits). The limestone aquifers are contained within the Madison Limestone, Jefferson Formation, and the Big Horn Dolomite. In addition to being unsuitable for ATEs owing to extreme depth in most areas, the limestone formations are also unsuitable owing to their secondary porosity caused by solution cavities.

The Paleozoic sandstone aquifers (Paleozoic clastics in Tables 1-1 and 1-2) are the Tensleep Sandstone, Quadrant Quartzite, Casper Formation, and the Frontier Formation. These formations have appreciable primary porosity because they are well-sorted sands. However, in most of the region, the Laramide Orogeny has folded these sediments so that they have extensive fracture zones and large well yields from the resulting secondary porosity. Additionally, the greatest portion of Paleozoic sandstones are found at excessive depths (3,000 feet below land surface) throughout the region. The outcrop areas along the mountain faults are the areas where most water wells penetrate these formations and often develop large volume flowing artesian wells. In

some localities, the water pressure at the ground surface is 300 pounds per square inch (Lowry, Lowham and Lines 1976; Whitcomb and Lowry 1968). The conditions of excessive depth, secondary porosity, and artesian conditions are undesirable for ATES, and therefore the Paleozoic sandstones are considered unsuitable for ATES. However, site-specific studies should be conducted, particularly for the Tensleep Sandstone, to best evaluate the ATES potential of these deposits.

AQUIFERS SUITABLE FOR ATES

Data gathered on aquifers in Region 1 indicate that there are some aquifers throughout the region which may be suitable for ATES. The data provided in Table 1-2 were reviewed with respect to the aquifer evaluation guidelines provided in the Introduction. Based upon the evaluation, an assessment was then made of the type of ATES storage that may be developed from an aquifer: large system chill, low or high temperature storage, or small system chill, low or high temperature storage. The following discussion of suitable aquifers is organized according to the format established in the Hydrogeologic Framework section of this chapter. Figure 1-4 provides a listing of the aquifers in Region 1 which may be suitable for ATES.

LARAMIDE CLASTICS

The sandstone formations deposited contemporaneously with the Laramide Orogeny appear to be regional water-bearing formations with ATES potential. As discussed in the section on aquifers unsuitable for ATES, these deposits are found within the intermountain valleys of the Middle Rocky Mountain province. Of particular interest are the Wind River Formation, the Duchesne Formation, and the Uinta Formation. These three formations contain sufficient sandstone interbeds to have been developed as major aquifers.

Detailed data for the hydrogeologic characteristics of these aquifers are not readily found in the literature for these formations. Table 1-2 presents the aquifer data available. The yield is generally below 500

AQUIFER	TYPES OF A.T.E.S. STORAGE	COMMENTS
Laramide Clastics — Middle Rocky Mountain Province	Small system — high, low, chill storage	The aquifer was judged suitable for A.T.E.S. based upon geology and data for well yield, transmissivity and depth. Data for other hydrologic characteristics were not available in the literature.

MAJOR AQUIFERS SUITABLE FOR A.T.E.S. IN REGION I

FIGURE I-4

gallons per minute and the transmissivity is commonly below 6,000 gallons per day per foot (Hood 1976; Whitcomb and Lowry 1968; and McCreevy, Hodson and Rucker 1969). These characteristics favor the development of a small system ATES facility. In many areas, the depth to the sandstone interbeds would be great enough to provide the hydrostatic confining pressure required for a high temperature system. Data for other hydrologic parameters were not obtainable in the literature. Site-specific studies are necessary to collect all the required data and evaluate the ATES potential of these aquifers.

REGION'S ATES POTENTIAL

The major aquifers of the Western Mountain Range region showing the best ATES potential are the undeformed sandstone interbeds within deposits common to the Tertiary Period. Discussed collectively as the Laramide clastics, the principal formations considered suitable for ATES are the Wind River Formation, the Duchesne Formation, and the Uinta Formations in the Middle Rocky Mountain province. Based upon data available for well yield, transmissivity and depth, these formations appear to have potential for small system chill, low or high temperature ATES facilities. The three formations listed above were selected on the basis of available data. Similar sandstone deposits occur throughout the Middle Rocky Mountain and Northern Rocky Mountain provinces. Site-specific studies for other formations of a similar geologic environment are needed to thoroughly assess the region's ATES potential.

Owing to the regional scope of this study, only the regional aquifers of Region 1 were considered for ATES potential and only the most recent and available literature was reviewed. Site-specific information could possibly reveal that aquifers other than the aquifers cited above have potential for ATES at particular localities. The purpose of this regional study is to determine the regional aquifers with the greatest potential for ATES and should not preclude site-specific investigations of smaller, more local aquifers.

REFERENCES CITED

- Boettcher, A. J., 1972, Ground-water occurrence in northern and central parts of western Colorado: Colorado Water Resources Circular No. 15, 25 p.
- #001 Boettcher, A. J., and Gosling, A. W., 1977, Water resources of the Clark Fork Basin upstream from St. Regis, Montana: Montana Bureau of Mines and Geology Bull. No. 104, 28 p.
- Brogden, R. F., and Giles, T. F., 1976, Availability and chemical quality of groundwater in the Crystal River and Cattle Creek drainage basins near Glenwood Springs west-central Colorado: U. S. Geol. Survey Water-Resources Investigations 76-70.
- Brogden, R. E., and Giles, T. F., 1977, Reconnaissance of ground-water resources in a part of the Yampa River Basin between Craig and Steamboat springs, Moffet and Routt Counties, Colorado: U. S. Geol. Survey Water-Resources Investigations 77-4 open file report.
- Cox, E. R., 1976, Water resources of northwestern Wyoming: U. S. Geol. Survey Hydrologic Investigations Atlas HA-558.
- #002 Drost, B. W., and Seitz, H. R., 1978, Spokane Valley-Rathdrum Prairie aquifer, Washington and Idaho: U. S. Geol. Survey Open File Report 77-829, 79 p.
- #003 Hammond, R. E., 1974, Groundwater occurrence and movement in the Athol area and the northern Rathdrum Prairie, northern Idaho: Idaho Dpt. Water Administration Water Inf. Bull. No. 35, 17 p., 8 figs.
- #004 Hood, J. W., 1976, Characteristics of aquifers in the northern Uinta Basin area, Utah and Colorado: State of Utah Dpt. Nat. Resources Technical Publication No. 53: 71 p.
- #005 Lowry, M. E., Lowham, H. W., and Lines, G. C., 1976, Water resources of the Bighorn Basin, northwestern Wyoming: U. S. Geol. Survey Hydrologic Investigations Atlas HA-512.
- #006 McGreevy, L. J., Hodson, W. G., and Rucker, S. J. IV, 1969, Ground-water resources of the Wind River Indian Reservation, Wyoming: U. S. Geol. Survey Water-Supply Paper 1576-I, 145 P.
- McKee, Bates, 1972, Cascadia; the geologic evolution of the Pacific Northwest: McGraw-Hill Company, 394 p.
- McMurtrey, R. G., Konizeski, R. L., and Brietkrietz, Alex, 1965, Geology and ground-water resources of the Missoula Basin, Montana: Montana Bureau of Mines and Geology Bull. No. 47, 35 p.

REFERENCES CITED (CONTINUED)

- Mintz, L. W., 1972, Historical Geology, the Science of a dynamic earth: earth: Charles E. Merrill Publ. Co., 783 p.
- Oakeshott, G. B., 1971, California's changing landscapes: McGraw-Hill Co. publ.
- Perry, E. S., 1962, Montana in the geologic past: Montana Bureau of Mines and Geology Bulletin No. 26, 78 p.
- Robinove, C. J., and Langford, R. H., 1963, Geology and ground-water resources of the Greybull River-Dry Creek area, Wyoming: U. S. Geol. Survey Water-Supply Paper 1576, 88 p.
- Walker, M. G., 1960, Water resources of the Nooksack River Basin and certain adjacent streams: State of Washington Dpt. Conservation, Div. Water Resources Water-Supply Bull. No. 12, 187 p.
- #007 Whitcomb, H. A., and Lowry, M. E., 1968, Ground-water resources and geology of the Wind River Basin area, central Wyoming: U. S. Geol. Survey Hydrologic Investigations Atlas HA-170.

GENERAL REFERENCES

The following references for Region 1 were reviewed, but are not cited in the report.

- Agnew, A. F., and Busch, R. W., 1971, Interstate ground-water aquifers of the State of Washington: State of Washington, Water Research Center Report No. 8, Part A-the physical situation, 66 p.
- Boettcher, A. J., and Wilke, K. R., 1978, Ground-water resources in the Libby area, northwestern Montana: Montana Bureau of mines and Geology Bull. No. 106, 36 p.
- California, State of, 1975, California's groundwater: California Dept. Water Resources, Bull. No. 118, pp. 29-33.
- Cline, D. R., 1969, Ground-water resources and related geology north-central Spokane and southeastern Stevens Counties, Washington: State of Washington Dpt. Water Resources Water-Supply Bulletin No. 27, 195 p.
- Coffin, P. L., Brietkrietz, Alex, and McMurtrey, R. G., 1971, Surficial geology and water resources of the Tobacco and Upper Stillwater River Valleys, Northwestern Montana: Montana Bureau of Mines and Geology Bull. No. 81, 48 p.
- Cooley, M. E., and Head, W. J., 1979-A, Hydrogeologic features of the alluvial deposits in the Greybull River Valley, Bighorn Basin, Wyoming: U.S. Geol. Survey Water-Resources Investigations Report 79-6, 38 p.
- Cooley, M. E., and Head, W. J., 1979-B, Hydrogeologic features of the alluvial deposits in the Nowood River drainage area, Bighorn Basin, Wyoming: U.S. Geol. Survey Water-Resources Investigations Open-File Report 79-1291, 55 p.
- Dion, M. P., and Whitehead, R. L., 1973, A groundwater monitoring network for Kootenai Flats, northern Idaho: Idaho Dpt. of Water Admin. Water Inf. Bull. No. 33, 41 p.
- Eakin, T. E., Price, Don, and Harrill, J. R., 1976, Summary appraisals of the Nation's ground-water resources-Great Basin Region: U. S. Geol. Survey Prof. Paper 813-G, 37 p.
- Ganus, W. J., 1973, Problems related to the evaluation of ground-water resources of the crystalline rock area, San Diego County, California: In, Ross, A., ed., Studies on the geology and geologic hazards of the greater San Diego area, California: San Diego Association of Geologists, pp. 111-118.
- Gates, J. S., et al, 1978, Ground-water conditions in Utah, Spring of 1978: Utah Dpt. of Nat. Resources Cooperative Investigations Report No. 17, 63 p.

GENERAL REFERENCES (CONTINUED)

- Hackett, O. M., Visher, F. N., McMurtrey, R. G., and Steinhilber, W. L., 1960, Geology and ground-water resources of the Gallatin Valley, Gallatin County, Montana: U. S. Geol. Survey Water-Supply Paper 1482, 282 p.
- Hood, J. W., 1977-A, Hydrologic evaluation of Ashley Valley, northern Uinta Basin Area, Utah: State of Utah Dpt. Nat. Resources Technical Publ. No. 54, 25 p.
- Hood, J. W., 1977-B, Hydrologic evaluation of the upper Duchesne River Valley, northern Uinta Basin Area, Utah: State of Utah Dpt. Nat. Resources Technical Publ. No. 57, 34 p.
- #008 Konizeski, R. L., McMurtrey, R. G., and Brietknetz, Alex, 1961, Preliminary report on the geology and ground-water resources of the northern part of the Deer Lodge Valley, Montana: Montana Bureau of Mines and Geology, Bull. No. 21, 24 p.
- #009 Konizeski, R. L., McMurtrey, R. G., and Brietkrietz, Alex, 1962, Preliminary report on the geology and ground-water resources of the southern part of the Deer Lodge Valley, Montana: Montana Bureau of Mines and Geology Bull. No. 31, 24 p.
- Konizeski, R. L., Brietkrietz, Alex, and McMurtrey, R. G., 1968, Geology and ground-water resources of the Kalispell Valley, northwestern Montana: Montana Bureau of Mines and Geology Bull. No. 68, 42 p.
- Robinoue, C. J., and Berry, D. W., 1963, Availability of ground-water in the Bear River Valley, Wyoming, with a section on chemical quality of the water by John G. Connor: U. S. Geol. Survey Water-Supply Paper 1539-V, 43 p.
- Robison, J. H., 1974, Availability and quality of groundwater in the Sutherlin area, Douglas County, Oregon: U. S. Geol. Survey Water-Resources Inv. 32-74.
- Robison, J. H., and Collins, C. A., 1977, Availability of quality of ground-water in the Drain-Yoncalla area, Douglas County, Oregon: U. S. Geol. Survey Water-Resources Inv. 76-105.
- Robison, J. H., and Collins, C. A., 1978, Availability and quality of ground-water in the Winston area, Douglas County, Oregon: U. S. Geol. Survey Water-Resources Inv. 77-28.
- Thomas, H. E., and Phoenix, D. A., 1976, Summary appraisals of the Nation's ground-water resources-California Region: U. S. Geol. Survey Prof. Paper 813-E, 51 p.

GENERAL REFERENCES (CONTINUED)

Van Denburgh, A. S. and Sanots, J. F., 1965, Groundwater in Washington its chemical and physical quality: State of Washington Dpt. Conservation, Div. Water Resources Water-Supply Bull. No. 24, 93 p.

#010 Walker, E. H., 1964, Groundwater in the Sandpoint region Bonner County, Idaho: U. S. Geol. Survey Water-Supply Paper 1779-1, 29 p.

Wyoming State Engineer, 1972, Water and related land resources of the Bighorn and River Basin, Wyoming: Wyoming Water Planning Program Report No. 11, 231 p.

Wyoming State Engineer, 1973, The Wyoming framework water plan: State Engineer's Office Wyoming Water Planning Program, 243 p.

Region 2. Alluvial Basins

REGION 2 - ALLUVIAL BASINS

INTRODUCTION

Region 2 is situated primarily in the southwestern portion of the United States (Figure 2-1) with an extension in Oregon and Washington. It contains the coastal and inter-montane valleys which are filled with unconsolidated sediments eroded from adjacent highlands (Pettyjohn 1979). This region has a range of annual precipitation from three inches in the southern deserts to more than 60 inches per year in the Puget Sound Lowland. The majority of the region is semi-arid to arid and receives less than 15 inches of precipitation annually. Generally, most of the water used in this region is groundwater drawn from unconsolidated sediments in alluvial basins. The alluvial basins have a variable sediment thickness ranging from a few hundred feet to several thousand feet.

The major physiographic subdivisions within this region are: 1) coastal valleys and ranges; 2) the Central Valley of California; 3) the Willamette Valley and Puget Sound Trough of Oregon and Washington; and 4) the basin and range area of California, Nevada, Oregon, Utah, Arizona, and Texas (Fenneman et al 1946). These physiographic provinces reflect the geologic and hydrologic framework of Region 2.

GEOLOGIC FRAMEWORK

The different physiographic provinces reflect the geologic framework of Region 2, and the general geology of each of the four different provinces is discussed below.

OUTLINE OF REGION 2

FIGURE 2-1

COASTAL VALLEY AND RANGE PROVINCE

The Coastal Valley and Range Province trends northwesterly along the Pacific Coast of California, bounded on the east by the Central Valley of California and Basin and Range Province and on the west by the Pacific Ocean. This province extends approximately 600 miles from the southern border of Oregon to the Mexican-American border. The width of this area varies from a few miles wide to approximately 140 miles.

The highest peaks within the coastal range seldom exceed 6,000 feet and crests average between 2,000 to 4,000 feet in elevation. Most of the crests are rounded by erosion while the jagged summit of the Sierra-Nevada reflects recent glaciation in the High Sierra, a process that did not reach the much lower coast ranges (Oakeshott 1971). The coastal range contains a very complex series of independent ranges and valleys; few of these are continuous for more than 100 miles.

Streams in the northern portion of this province flow northwest or southeast, rather than west, as they do in the southern portion of the province. The largest stream, in terms of runoff, is the Eel River, which drains the Mendicino Range in a north to northwesterly direction into Humboldt Bay at Eureka. The Russian River also originates in the Mendicino Highlands but runs southeasterly to enter the Pacific Ocean just north of Point Reyes. The longest continuous valley in the coastal ranges is the Salinas Valley. The Salinas River follows the Salinas Valley northwesterly to Monterey Bay.

In the southern portion of the province the streams flow westward. These southern streams do not carry large volumes of water and most are intermittent. Among the larger streams are the Los Angeles, San

Gabriel, Santa Ana, Santa Margarita, San Luis Rey and the San Diego rivers. These rivers are contained in large valleys and seldom have any appreciable stream flow because of the semiarid to arid climatic conditions.

The geologic framework can be divided into two distinct sub-provinces: 1) the geology of the coastal valleys; and 2) the geology of the coastal ranges. The following discussion outlines the basic geology of each of the sub-provinces within the Coastal Valley and Range Province.

Coastal Valleys

The lowland areas of the Coastal Valley and Range Province are filled with unconsolidated material. The majority of stratigraphic units in the coastal valleys grade oceanward from partly alluvial deposits to entirely marine units. The alluvium under the majority of the basins is very fine-grained and composed predominantly of thick sequences of marine and brackish water clay layers. The sand and gravel stringers within the marine deposits vary in grain-size both horizontally and vertically over their extent.

Coastal Ranges

The highland areas of the Coastal Valley and Range Province consist of folded and faulted sedimentary and metamorphic rocks. The topography is marked by major structural features (i.e. faults, associated fractures and joint sets). The highland morphology is generally related to weathering and erosional effects on the structural fabric of the underlying bedrock. Over most of the highland area, the bedrock

is covered by a variable amount of in-situ weathered material with the thickest deposits being located in meadows and valleys. The thickness of the unconsolidated material within the highland valleys varies from less than 10 feet to over 200 feet and consists generally of poorly stratified gravel-sand-silt mixtures.

CENTRAL VALLEY OF CALIFORNIA PROVINCE

The Central Valley of California forms a north-south trending basin approximately 400 miles long and averaging about 50 miles wide. This structural trough is essentially flat lying and lies at elevations which vary from a few feet to a few hundred feet above sea level. The valley is bounded on the west by the coast range and on the east by the Sierra-Nevada. The valley rises very gradually eastward towards the gently sloping western foothills of the Sierra-Nevada. The surface of the granitic bedrock of the Sierra-Nevada is tilted gently westward and extends a great distance out under the valley. The rise to the coastal ranges on the west is much more abrupt and the complex bedrock formations dip steeply eastward under the valley. The alluvial sediments filling the valley range from more than ten miles deep on the west side and thin gradually to just a surface covering on the east side. Interbedded gravel, sand, silt and clay strata of Quaternary Age were derived predominantly from the Sierra-Nevada Range (Oakeshott 1971).

The northern portion of the valley is called the Sacramento Valley and is drained by the Sacramento River and its tributaries, which drain the mountains to the north and east of the central valley. The southern portion of the valley is commonly referred to as the San Joaquin

Valley and is drained by the San Joaquin River. In the southern portion of the San Joaquin Valley are two closed basins, Tulare Lake and Buena Vista Lake. In wet years, during flood times both basins form one vast lake and drain northward to San Francisco Bay via the San Joaquin River. The Sacramento and San Joaquin rivers combine to form a large delta east of San Francisco Bay which in turn drains into the Pacific Ocean.

During much of the Cretaceous and Tertiary Periods, the valley was the site of marine deposition and as much as 2,000 to 3,000 feet of sediments accumulated. Overlying the marine sediments are continental deposits of late Tertiary and Quaternary age which in specific areas exceed 10,000 feet in thickness. The continental deposits are generally of fluvial origin, although locally, lacustrine deposits make up a substantial portion of the non-marine section. The fluvial deposits consist of discontinuous, lenticular bodies of gravel, sand, and silt laid down in stream channels and discontinuous sheetlike bodies of silt and clay formed by overflow periods. The lacustrine deposits consist of well-sorted silts and clays with well-sorted sand lenses near mouths of major streams.

Few laterally continuous strata are present in the non-marine section. However, a strata of well-sorted lacustrine diatomaceous clay 10 to 100 feet thick is found in the central portion of the San Joaquin Valley and underlies approximately 5,000 square miles of the valley (Davis 1959).

WILLAMETTE VALLEY - PUGET SOUND TROUGH PROVINCE

The Willamette Valley - Puget Sound Trough area is a long, northerly trending valley bounded on the east by the Cascade Range and on the west by the Olympic Mountains and Oregon Coastal Range. Its northern end is occupied by Puget Sound and its southern end by the Willamette Valley in Oregon. This trough extends approximately 350 miles in length and averages 50 miles wide at the northern end, narrowing irregularly toward the south and terminating where the Cascades and the Coastal Ranges meet. The altitude of the valley rarely exceeds 500 feet. Sediments within this area were deposited in a structural trough. Consolidated rocks of Eocene to Miocene age, chiefly volcanic lava flows, pyroclastic rocks and some sedimentary strata, are exposed in the foothills of the Cascades and underlie the unconsolidated alluvial fills to the west (Mundorff 1964). The younger (Pliocene to Recent) unconsolidated sediments were deposited predominantly by fluvial processes with minor deposits of lacustrine and glacial origin, as well as basalt flows with a local areal extent.

In the southern portion of the area (the Willamette Valley), the oldest unconsolidated rock unit is the Troutdale Formation. This formation consists predominantly of consolidated clay, silt and fine-grained sand but includes some lenses of coarser sand and gravel. Overlying the Troutdale Formation in several localities are basaltic lava flows commonly referred to as the Boring Lava.

Glacial drift, including till, glacio-fluvial outwash and deposits of glacial lakes and ponds blanket areas in the Puget Trough area and the Willamette Valley.

BASIN AND RANGE PROVINCE

The basin and range area, as described in this report, is the same as the physiographic province described by Fenneman, et al. (1946). This area includes the eastern portion of California, the majority of Nevada, the southern portions of Arizona and New Mexico, the southwestern portion of Texas and the southeastern portion of Oregon. There are at least 250 valleys within the basin and range area, some of which are topographically closed, the majority of which are interconnected either by surface or subsurface flow and drain into the major river systems. A major portion of the Basin and Range Province is located in a topographically closed area of Nevada and Utah commonly referred to as the Great Basin. The Great Basin area is characterized by generally parallel, north to northeast trending mountain ranges separated by broad alluviated desert basins. The mountain ranges are generally 40 to 80 miles long spaced 15 to 25 miles apart (Eakin 1976). Usually there is an intermediate slope from the valley floors to the bordering mountain range formed by coalescing alluvial fans. Gradients of these slopes vary from a few tens of feet to several hundred feet per mile.

The basin and range area is characterized by ranges of uplifted, fault-bounded blocks and basins of sediment-filled downdropped fault blocks. Consolidated rocks exposed in the ranges and underlying the basins at depth include clastic and carbonate sediments and intrusive and extrusive igneous rocks ranging in age from Precambrian to Tertiary. Unconsolidated and partially consolidated alluvial fills of Quaternary age generally overlie the basins' consolidated bedrock. The older, partially consolidated alluvial deposits are exposed along basin

margins and are generally somewhat cemented, folded, and faulted. The younger basin-fill alluvium consists of thick and extensive deposits of flat-lying, unconsolidated sediments. These deposits contain the full range of depositional environments from coarse-grained sands and gravels to the evaporite deposits of freshwater lakes.

HYDROGEOLOGIC FRAMEWORK

As stated in the Introduction, the hydrogeologic framework of Region 2 corresponds to the four different physiographic provinces. The following discussion outlines the general hydrogeology of each of the four physiographic provinces of Region 2.

COASTAL VALLEY AND RANGE PROVINCE

Just as the geologic framework of the Coastal Valley and Range province may be divided into two distinct sub-provinces, so may the hydrogeologic framework be divided into: 1) the hydrogeology of the coastal valleys; and 2) the hydrogeology of the coastal ranges. The following discussion outlines the hydrogeology of each of the sub-provinces.

Coastal Valleys

The sediments comprising the water-bearing formations of the coastal valleys are unconsolidated to semiconsolidated and contain groundwater in the primary porosity volumes. Grain-size varies from clay to gravel and reaches a maximum of boulder size in certain areas. Quaternary alluvium is generally the most important water-bearing formation within the coastal valleys. Permeability of the alluvium is

relatively high, ranging from 1 to 100 darcys for the sand and gravel aquifers to less than 0.01 darcys for the silts and clays or the aquicludes (Davis and Dewist 1966).

Groundwater in the coastal valleys is essentially unconfined to semi-confined. In some areas the confining silt and clay lenses near the ocean result in localized artesian conditions. The deeper confined aquifers usually contain water under artesian pressure from the broad lateral extent of the capping clay strata and the high elevation of the recharge (forebay) area. Figure 2-2 provides a diagrammatic cross section of the ground-water flow regime in the coastal valleys.

Within the coastal valley area, groundwater temperatures range from 24°C to 96°C with 60°C recorded at Boyes Hot Springs in Sonoma Valley. Total dissolved solids are generally less than 800 milligrams per liter (mg/l) with localized areas exceeding 11,000 milligrams per liter (mg/l). The major water type is calcium-magnesium bicarbonate with minor amounts of sodium sulphate and chloride occurring in some basins (Calif. Dept. Water Resources 1978). Sea water intrusion is the limiting factor in developing the coastal basin areas and major degradation has already occurred in Salinas Valley where both shallow and deep aquifers have sea water intrusion problems.

Coastal Ranges

Bedrock exposed in the highland areas of the coastal ranges area is generally crystalline rock and has a low permeability. Within the highland area, groundwater exists largely in secondary porosity openings formed by fractures, joints, shear zones and faults. Secondary porosity provides minimal storage space and avenues for movement of

DIAGRAMMATIC CROSS-SECTION OF GROUND-WATER FLOW REGIME IN COASTAL VALLEYS

Adopted from Haley, J.M., 1953, Santa Cruz Area

FIGURE 2-2

groundwater. The non-uniform occurrence of secondary porosity in any given rock type or geographic area, restricts the ability of these rocks to yield groundwater to wells, resulting in well yields that are quite variable and dependent on local structural conditions.

Ganus (1973) suggests the concept of two different unconfined ground-water systems developing in crystalline rock areas. The downward movement of water from the shallow water table through occasional and frequently plugged fractures is probably insufficient to keep the deeper fractures saturated. As a result, the deeper system develops an independent flow system and water level. Small springs from both the upper and lower ground-water aquifers can be expected.

The valleys within the highland areas of the Coastal Ranges are the major source of groundwater for consumptive use. Average well yields within this area vary from less than 5 gallons per minute to greater than 100 gallons per minute. Owing to the variable sediment type and thickness of the unconsolidated material at each location, the aquifers in the valleys of the highland areas of the coastal ranges are of sub-regional extent. The hydrologic conditions and well yield at a particular location cannot be predicted prior to drilling.

CENTRAL VALLEY OF CALIFORNIA PROVINCE

Within the Central Valley of California province three distinct aquifer groups occur. In downward succession they are: 1) unconfined and semi-confined fresh water aquifers occurring in the alluvial deposits of Recent Age, and in the southern portion of the valley the alluvial aquifers overlie widespread lacustrine strata; 2) confined fresh water aquifers below the lacustrine deposits (South San Joaquin Valley

Aquifer and in structural traps in the northern portion of the valley (Woodland Aquifer); and 3) a body of saline connate water contained in marine sediments underlying the freshwater body throughout the valley.

Recharge to the confined aquifers occurs chiefly from unconfined and semi-confined deposits beyond the lateral boundaries of the confining strata. Additional water is supplied from slow downward percolation of water through confining beds in areas where artesian head in the confined aquifers has been drawn down by extensive pumping (Green 1964).

Ground-water temperature ranges from 13°C to 24°C in the Sacramento Valley to 7°C to 40°C in the San Joaquin Valley. Total dissolved solids vary from less than 55 milligrams per liter in the Sacramento Valley to more than 10,000 milligrams per liter in the San Joaquin Valley. The predominant water type is calcium bicarbonate with some areas on the west side of the San Joaquin Valley having sodium sulfate (Calif. Dept. of Water Resources 1978). Extensive ground-water pumping has caused significant land subsidence problems predominantly in the central and southern portions of the Central Valley of California province. Saline water has been encountered at shallow depths generally within the delta area of both the Sacramento and San Joaquin Rivers.

WILLAMETTE VALLEY - PUGET SOUND TROUGH PROVINCE

The alluvial deposits of Recent and Pleistocene age yield most of the groundwater throughout the Willamette Valley - Puget Sound Trough with average well yields ranging from 100 gallons per minute to more

than 1,000 gallons per minute (Helm 1968). The majority of the high yielding aquifers (greater than 50 gallons per minute) are primarily unconfined and occur in the more recent alluvial deposits. Confined aquifers of small areal extent occur at depths in the Troutdale Formation south of Portland (Foxworthy et al. 1964).

The alluvial aquifers of Recent and Pleistocene age are hydrologically complex. The sands and gravels commonly interfinger with silts and clays. Because of the rapid facies changes, the aquifers associated with the alluvial sands and gravels usually have variable hydrologic conditions from place to place; the aquifers range from confined to unconfined over short distances, and the thicknesses of the aquifers are not uniform.

In the foothills of the Willamette Valley many of the wells tap isolated perched horizons. Many wells situated high on ridges have water levels less than 100 feet below the ground surface (Hampton 1968). Average well yields within the foothill area varies from 10 to 20 gallons per minute. The highest yielding wells (few hundred gallons per minute) develop groundwater from rubbly zones between lava flows.

In general, ground-water quality of the Willamette Valley - Puget Sound Trough is good to excellent with moderately mineralized (100-200 milligrams per liter (total dissolved solids) groundwater occurring in the Willamette Valley area and less than 250 milligrams per liter in the Puget Sound Trough. In the Puget Sound Trough, saline water is encountered at shallow depths and represents connate sea water. Locally, iron concentrations are troublesome (Pettyjohn 1979).

BASIN AND RANGE PROVINCE

In the Basin and Range province a large amount of groundwater is stored in the consolidated rocks that occur both in the mountain ranges and beneath the valley alluvium. These aquifers generally are not continuous and contain a multitude of local barriers formed by faults or lithologic changes. Carbonate and volcanic rocks compose the majority of the consolidated rock reservoirs.

Carbonate rocks, in most areas where they occur, are highly permeable and transmit water through fractures (secondary porosity) in several multi-valley ground-water systems (Eakin 1976; Eakin et al. 1967; Winograd and Thordarson 1975). Areas of known carbonate aquifers are generally found in the eastern portion of the basin and range area (Eakin et al. 1967). In some areas, volcanic rocks have fractures and interflow openings that store and transmit large quantities of groundwater. The discharge from these aquifers sustains the flow of many streams and numerous springs near bedrock-alluvial contacts. Areas with known volcanic aquifers include Pavant Valley, Curlen Valley, Winnemucca area, and the Fallon area (Eakin et al. 1967).

The valley alluvial aquifers are contained within the more permeable sands and gravels in the basins and in most places provide the only supply of groundwater available for large scale use. Of the more than 250 alluvial basins identified in this area only approximately 25 percent have aquifers with estimated yields of 50 gallons per minute or better (Eakin et al. 1967).

Artesian conditions occur in the valley alluvium where layers of silt and clay are abundant enough to confine or partially confine groundwater in the underlying deposits. Specific data on specific

alluvial aquifers and their hydraulic characteristics are generally not available.

Eakin et al. 1967 describes the groundwater flow systems in these alluvial basins in terms of surface and subsurface flow between the basins. Within the basin and range area, 11 are considered closed basins that have well yields greater than 50 gallons per minute. Closed basins are described as basins where no surface or subsurface flow out of the basin is recognized. These major basins are: Galls Valley, Estancia Basin, Buena Vista Valley, Edmonds Creek Valley, Big Smokey Valley, Grass Valley, Smith Creek Valley, Sena Valley, Animas Basin, Playas Basin and Memhaus Basin. Of all the closed basins mentioned, only Big Smokey Valley has been studied in any detail (Rush and Schraur 1970). Rush and Schraur found that this basin also has subsurface outflow because of the high secondary porosity of the underlying carbonate bedrock.

The chemical quality of the groundwater in the Basin and Range Province varies from freshwater (less than 1,000 milligrams per liter) to brine (more than 35,000 milligrams per liter). Generally, along the margins of most valleys, the groundwater is of good quality. Saline water occurs locally where the aquifer includes rocks containing large quantities of soluble salts and also within undrained closed basins and sinks. In much of the area in southern Nevada, the fluoride concentration in groundwater exceeds Public Health Service Standards for drinking water and is probably associated with an extensive volcanic tuff in that region.

MAJOR AQUIFERS

For the purpose of this study, a major aquifer is identified as an aquifer with significant areal extent that can sustain typical well yields of at least 50 gallons per minute throughout the extent of the aquifer. The major aquifers are either suitable or unsuitable for thermal energy storage, and a discussion of each aquifer's evaluation is presented in the following sections. The previous sections of this chapter described the geologic and hydrogeologic framework and introduced the common aquifers of Region 2.

The Hydrogeologic Framework section of the chapter described the general occurrence of groundwater and discussed many water yielding rock formations regardless of their areal extent or yield characteristics. Table 2-1 provides a listing of the major aquifers in the region.

Specific data pertaining to those major aquifers' quantitative properties thought to be suitable for ATEs are tabulated and listed according to porosity group in Table 2-2. The qualitative geologic characteristics of each hydrogeologic environment are generalized and presented in Table 2-2. The specific reference for which quantitative data is cited can be identified by checking the title of the numbered reference given after each set of data.

AQUIFERS UNSUITABLE FOR ATES

All of the major aquifers of Region 2 have been evaluated according to the guidelines established in the Introduction. On the basis of this evaluation many of the aquifers have been judged as generally unsuitable for ATES. In most cases, site-specific studies are needed to more fully evaluate the ATES potential of each aquifer. The aquifers judged unsuitable at this time for ATES are discussed below, together with the justification for their unsuitability.

The aquifers are presented by each of the four different physiographic provinces of Region 2. Figure 2-3 provides a listing of the major aquifers in Region 2 considered unsuitable for ATES.

COASTAL VALLEYS AND RANGES PROVINCE

Coastal Valleys

Aquifers found in the coastal valleys occur predominantly in unconfined sand and gravel lenses interbedded with silts and clays of both marine and non-marine origin. Generally, the complex facies relationships result in discontinuous water-bearing strata with variable hydraulic gradients and aquifer thicknesses. The variable hydrologic conditions tend to minimize the ATES potential for the coastal valley aquifers. The few confined aquifers in the coastal valleys (i.e. Eureka Bay, San Francisco Bay, Santa Cruz area, and Ventura Bay) also have discontinuous confining layers of variable thicknesses. These aquifers are characterized by low permeability that minimizes the ATES potential. There may exist local confined ground-water systems in the coastal valleys which have ATES potential, but site-specific studies will be necessary to identify these areas.

AQUIFER	REASONS FOR UNSUIT— ABLE RECOMMENDATION	COMMENTS
Localized Alluvial Sands and Gravels	Rapid facies changes make hydrologic condi- tions vary from place to place; therefore aquifers are sub-regional in ex- tent. Alluvium, in general, yields less than 50 gpm.	Site-specific studies may provide information that proves an alluvial aquifer is suitable for A.T.E.S. at a particular location.
Volcanic Crystalline and Carbonate Bedrock	Fracture Porosity	All aquifers with fracture porosities are considered unsuitable for A.T.E.S. at this time owing to the random and unpredictable volumes of stored water in these aquifers.

MAJOR AQUIFERS UNSUITABLE FOR A.T.E.S. IN REGION 2

Coastal Ranges

Groundwater within the coastal ranges exists predominantly within small alluvial basins and secondary openings in bedrock. The sands and gravels of the small alluvial basins have very limited areal extent and are discontinuous water-bearing strata. Well yields are generally less than 50 gallons per minute. Water-bearing zones within the crystalline bedrock are contained in the secondary porosity openings and are frequently structurally controlled. Secondary porosity aquifers are considered unsuitable for ATEs because the storage and movement of groundwater is highly variable and does not comprise a suitable storage and transport media for thermal energy.

CENTRAL VALLEY OF CALIFORNIA PROVINCE

The alluvial aquifers of Recent age located in the Central Valley of California in general are considered at this time to be unsuitable for ATEs. There was no specific hydrologic data available in the literature for these aquifers. Therefore, an assessment of the aquifers' suitability was made by evaluating what is known about the geology of these aquifers. The sedimentary depositional environment associated with rivers and streams provides for rapid facies changes. As a result of rapid facies changes, the sand and gravel aquifers are generally not widespread and hydrogeologic conditions may change markedly over the extent of the aquifer. In some locations, an alluvial aquifer may be confined and unconfined in other areas.

Site-specific studies may establish that alluvial sands and gravels in the Central Valley of California at a particular location may be suitable for ATEs. However, the regional scope of this study dictates that

in general, these sub-regional aquifers may be considered unsuitable for ATEs.

WILLAMETTE VALLEY - PUGET SOUND TROUGH PROVINCE

Aquifers in this area occur in alluvial basins, glacial deposits, and volcanic flows. Aquifers in the alluvial basins and glacial deposits are contained within water-bearing sand and gravel lenses. The complex facies relationships, variable gradients and thicknesses as well as localized areal extent, are factors which give the sand and gravel deposits an undesirable rating for ATEs development. Those aquifers found in the volcanic rocks occur within interflow zones, fractures and joints. Aquifers associated with the volcanic rocks generally have high secondary porosity which results in minimal potential for ATEs development. Secondary porosity is undesirable because high transmissivity values and low predictability of groundwater movement in fractures and cavities results in adverse effects on the thermal recovery economics.

AQUIFERS SUITABLE FOR ATES

Data gathered on aquifers in Region 2 indicate that there are few aquifers throughout the region suitable for ATES. The data provided in Table 2-2 were reviewed with respect to the aquifer evaluation guidelines provided in the Introduction. Based upon the evaluation, an assessment was then made of the type of ATES storage that may be developed from an aquifer: large system chill, low or high temperature storage, or small system chill, low or high temperature storage. Aquifers that may be suitable for ATES are discussed below by the physiographic province in which they occur. Figure 2-4 provides a listing of the major aquifers in Region 2 considered at this time to be suitable for ATES.

CENTRAL VALLEY OF CALIFORNIA

Within the Central Valley of California is an area of potential for ATES development. This area is situated in the southwest portion of the San Joaquin Valley in sediments of alluvial origin. This area extends along the western side of the San Joaquin Valley from the Sacramento area southward to Bakersfield, California (Figure 2-1).

Underlying approximately 5,000 square miles of the valley is a continuous stratum of well-sorted lacustrine diatomaceous clay 10 to 150 feet thick, found approximately 300 feet deep throughout the area (Davis et al. 1959). This stratum is commonly referred to as the Carconan Clay Member of the Tulane Formation. This clay stratum forms an important confining layer within the southern portion of the Central Valley. Effective confinement occurs also in areas beyond the known extent of the diatomaceous clay, notably along the southeastern

AQUIFER	TYPES OF A.T.E.S. STORAGE	COMMENTS
Southern San Joaquin Valley	Large System – high, low, chill storage	Owing to the variable conditions within the aquifer, site-specific studies will provide information as to the type of A.T.E.S. storage that should be developed in a given area.
Newankum Artesian Basin	Small system – high, low, chill storage	Yields are generally insufficient (<500 gpm) for development of a large system A.T.E.S. facility. Data are insufficient at this time to determine the aquifers' real potential for A.T.E.S. Site-specific studies are needed.
Closed Basins of Basin and Range Province	Large system – high, low, chill storage Small system – high, low, chill storage	There are insufficient data at this time to make an adequate assessment of the aquifers' potential for A.T.E.S. It may be found that there are areas of the aquifers which may be suitable for each of the different types of storage.

MAJOR AQUIFERS SUITABLE FOR A.T.E.S. IN REGION 2

and southern margins of the valley, and probably represents a shoreward environment of deposition of the same age. Confinement in the extreme southern portions of the valley is caused by a thick section of poorly-sorted fluvial deposits of low permeability rather than by a single confining bed of wide extent. The lithology of the sediments underlying the confining units are of alluvial origin and poorly defined.

The extent of the confined aquifer in most places can be readily defined. Near the margins of the valley, however, the boundaries are indefinite and not well defined because of intermixing of water from both upper unconfined and lower confined aquifers.

Movement of groundwater within this confined zone is generally from the foothills of the coastal range on the west and the Sierra Nevada on the east. All flow is toward the axis of the valley. Hydraulic gradients are considered gentle and are only a few feet to the mile (Davis and Poland 1957). Within the confined aquifer, heavy pumping has drawn down the piezometric level as much as several hundred feet. The long-continued decline in artesian head is the result of long term withdrawal in excess of replenishment. Seasonal fluctuations in artesian pressure and the hydraulic gradient are caused generally by changes in the rate and distribution of pumping.

Groundwater temperatures within the Central Valley area vary from 7°C to 40°C and total dissolved solids range from less than 55 milligrams per liter to more than 10,000 milligrams per liter. The predominant water type is calcium bicarbonate with localized areas of sodium sulfate (Calif. Dept. of Water Resources 1978).

Specific aquifer parameters (i.e. transmissivity, porosity, permeability, etc.) need to be developed for this area. However, the large

lateral extent, great thickness of the overlying confining layer and low hydraulic gradients justify further field investigation as a potential ATES site.

The South San Joaquin Valley area aquifer would probably be most suitable for chill or low temperature storage. The potential for high temperature storage should be examined with regard to the possibility of breaching the confining layer. The high yields obtained from this aquifer would allow its use for large ATES systems.

Some limitations to this aquifer's potential are: 1) the aquifer may not exhibit complete confinement conditions throughout its areal extent; and 2) the aquifer is used heavily for domestic and irrigation water suppliers, which results in a widespread cone of depression surrounding the well fields and causes the potentiometric surface hydraulic gradient to fluctuate with seasonal pumping rates.

WILLAMETTE VALLEY - PUGET SOUND TROUGH

The Newaukum Artesian Basin is within the Puget Sound Trough in southwestern Washington, approximately 35 miles south of the southern end of Puget Sound and adjacent to the foothills of the Cascade Range. The basin covers an area of approximately 25 square miles (Weigle and Foxworthy 1962). The basin consists of a large synclinal structure is occupied by the Newaukum River and the lower reaches of its north and south forks. The syncline is commonly referred to as the Napavine syncline (Snively et al. 1958). The axis of the syncline trends south-east, paralleling the course of the Newaukum River. Large supplies of high quality groundwater are obtained from an artesian aquifer in the non-marine sedimentary rocks of this basin.

The rock unit that yields the ground-water supply is a non-marine unit of Miocene and Pliocene age. This unit generally consists of clay and silt with lenses of sands and gravels yielding moderate amounts of water (at least 100 gallons per minute). Confinement of the water within the basin area is from impermeable glacial sediment above the aquifer and the folded sediments of Tertiary Age below.

Recharge to the non-marine unit within the basin is chiefly by precipitation in upland plains where the unit is in hydraulic contact with more recent sediments. In parts of the basin, the artesian pressure is great enough to cause wells tapping the unit to flow at land surface.

Fairly substantial yields are obtained from wells that tap only the uppermost part of the non-marine unit in the artesian basin. Yields of 100 to 200 gallons per minute from wells 250 feet deep are common. Although some wells flowed several hundred gallons per minute when first drilled, most have required installation of pumps to develop their full potential. The piezometric surface in wells tapping the non-marine unit ranges from about 50 feet above the land surface to 25 feet or more below (Weigle and Foxworthy 1962).

Specific hydrologic data for the aquifer were not available in the literature. Therefore, an assessment was made on the aquifer's suitability for ATES based upon what is known about the general geology of the aquifer. Extensive site-specific studies will have to be conducted before developing an ATES facility. Based upon the moderate well yields (generally less than 500 gallons per minute), the aquifer is probably only suitable for a small ATES system.

BASIN AND RANGE AREA

Within the basin and range area of Region 2 are several (11) closed basins that could possibly have potential for ATEs development. Generally, the closed basins occur within the northwestern portion of Nevada and the southwestern portion of New Mexico (Eakin et al 1967; Yates 1967).

Closed basins are areas with no surface flow across boundaries and all groundwater is discharged ultimately by evapotranspiration. These areas are typified by valleys with wet playas and phreatophyte stands in shallow groundwater areas. The ground-water gradient is always toward the center or low part of the valley.

Closed basins included in this category are: Big Smokey Valley, Edwards Creek Valley, Buena Vista Valley, Gubbs Valley, Grass Valley, Smith Creek Valley, Sano Valley of Nevada and Estancia Basin, Animas Basin, Playas Basin, and Membres Basin of New Mexico.

All of these basins are generally alluvial-filled grabens, bounded by impermeable bedrock. The majority of data available (Eakin et al. 1967; Yates 1967) included aerial extent and storage (Table 2-2).

Rush et al (1970) investigated the Big Smokey Valley area of Nevada and concluded that it was interconnected hydraulically with the surrounding basins through subsurface flow. This may be the case with the remaining ten closed basins.

Specific hydrologic data for the aquifers of the closed basins are generally unavailable in the literature. There was no information available in the literature suggesting that the aquifers are unsuitable for ATEs. Extensive site-specific studies are needed to adequately assess the real ATEs potential of the closed basins' aquifers.

REGION'S ATES POTENTIAL

Based upon the literature review, there are few aquifers in Region 2 with potential for ATES. The alluvial aquifers of Region 2 have a limited data base upon which to assess their ATES potential. Alluvial basins typically have rapid facies changes and therefore the aquifers associated with the sand and gravels in these basins are sub-regional in their extent. The areas of Region 2 that appear to have the most potential for ATES are: 1) the south San Joaquin Valley of the Central Valley of California province; 2) the Newaukum Artesian Basin of the Willamette Valley - Puget Sound Trough province; and 3) the closed basins of the Basin and Range province. In all cases, site-specific information is needed before development of an ATES facility is considered.

Owing to the regional scope of this study, only the regional aquifers of Region 2 were considered for ATES potential, and only the most recent and available literature was reviewed. It is possible that site-specific information will prove that aquifers other than the aquifers cited above have potential for ATES at particular localities. The purpose of this regional study is to determine the aquifers which appear to have the greatest potential for ATES and should not preclude site-specific investigations.

REFERENCES CITED (CONTINUED)

- Mundorff, M. J., 1964, Geology and ground-water conditions of Clark County, Washington, with a description of a major alluvial aquifer along the Columbia River: U. S. Geol. Survey Water-Supply Paper #1600.
- Oakeshott, G. B., 1971, California's changing landscapes: A guide to the geology of the state, McGraw Hill, Inc. N. Y.
- Pettyjohn, W. A., 1979, A ground-water quality Atlas of the United States: prepared under research section of the National Water Well Association for the National Demonstration Water Project.
- Rush, F. E. and Schraur, C. V., 1970, Water Resources of Big Smokey Valley, Lander, NYE and Esmeralder Counties, Nevada: State of Nevada Department of Conservation and National Resources, Division of Water Resources, Water Resources Bulletin #41.
- Snively, P. D., et al, 1958, Geology and Coal Resources of the Centralia-Chehalis District, Washington, with a section on Microscopical character of the Centralia-Chehalis Coal: Washington State Geological Survey, Bulletin #1053, 159 p.
- #013 Weigle, J. M., and Foxworthy, B. L., 1962, Geology and ground-water resources of west-central Lewis County, Washington: State of Washington, Division of Water Resources, Water-Supply Bulletin #17.
- Winograd, I. J., Thordarson, W., 1975, Hydrogeologic and hydrochemical framework south central Great Basin, Nevada, California: with special reference to the Nevada Test Site.
- #014 Yates, J. C., 1967, Water resources of New Mexico, occurrences, development and use: New Mexico State Engineer Office.

REFERENCES CITED

- California Department of Water Resources, 1978, Evaluation of ground-water resources, Sacramento Valley: State of California, Division of Water Resources, Bulletin No. 118-6.
- #011 Davis, G. H., et. al., 1959, Ground-water conditions and storage capacity in the San Joaquin Valley, California: U. S. Geol. Survey Prof. Paper No. 813-R.
- Davis, G. H., and Poland, J. H., 1957, Ground-water conditions in the Mendota Huron Area, Fresno and Kings County, California: U. S. Geol. Survey Water-Supply Paper No. 1360-G.
- Davis, S. N., and DeWeist, 1966, Hydrogeology: John Wiley & Sons, Inc., N. Y.
- #012 Eakin, T. E., 1976, Summary appraisals of the nation's ground-water resources - Great Basin Region: U. S. Geol. Survey Prof. Paper No. 813-G.
- Eakin, T. E., et. al., 1967, Water resources appraisal of Steptoe Valley, White Pine and Elko Counties, Nevada: Water Resources Reconnaissance series report No. 42, State of Nevada, Department of Conservation and Natural Resources.
- Fenneman, N. M., et. al., 1946, Physical divisions of the United States: U. S. Geol. Survey map, scale 1:7,000,000.
- Foxworthy, B. L., et. al., 1964, Records of wells and springs, water levels and chemical quality of ground-water in the East Portland area, Oregon: State of Oregon Ground-Water Report No. 3.
- Ganus, W. J., 1973, Problems related to the evaluation of ground-water resources of the crystalline rock area, San Diego County, California: In Ross, A., ed., Studies on the geology and geologic hazards of the greater San Diego area, California. San Diego Association of Geologists, pp. 111-118.
- Green, J. H., 1964, The effect of artesian - pressure decline on confined aquifer systems and its relation to land subsidence: U. S. Geol. Survey Water-Supply Paper No. 1779-T.
- Hampton, E. R., 1968, Records of wells, water levels and chemical quality of ground-water in the Molalla-Salem slope area, northern Willamette Valley, Oregon: State of Oregon coop with United States Geological Survey Ground-Water Report #2.
- Helm, D. C., 1968, Records of wells, water levels and chemical quality of water in lower Santiam River basin, middle Willamette Valley, Oregon: State of Oregon coop with United States Geological Survey Ground-Water Report #13.

GENERAL REFERENCES

The following references for Region 2 were reviewed but are not cited in the report.

Babcock, H. M., 1975, Annual report on ground-water in Arizona with emphasis on Gila Bend basin, McMullun Valley, and southeastern part of Harquahala Plains-spring 1973 to spring 1974: District Chief of U. S. Geol. Survey in Arizona, Arizona Commission Bulletin No. 9.

Broadhurst, W. L., et. al., 1949, Public water supplies in western Texas: Texas Board of Water Engineers coop with U. S. Geol. Survey.

Broadhurst, W. L., et. al., 1955, San Joaquin County investigations: State of California, Division Water Resources Bulletin No. 11.

Broadhurst, W. L., et. al., 1964, Shasta County investigations: State of California, Division of Water Resources Bulletin No. 22.

Broadhurst, W. L., et. al., 1975, California's ground-water: California Department of Water Resource Agency, Bulletin No. 118.

Broadhurst, W. L., et. al., 1978, The nation's water resources, 1975-1000, Vol. 4, California Region: United States Water Resources Council, 1978, 2nd National Water Assessment.

California Department of Water Resources, 1953, Ventura County, Investigations: California State Water Resource Board, Bulletin No. 12, Volumes 1 and 2.

California Department of Water Resources, 1957, Lake County Investigations: State of California, Division of Water Resource, Bulletin No. 14.

California Department of Water Resources, 1968, Evaluation of ground-water resources, south San Francisco Bay, Vol. 3, Northern Santa Clara County area: State of California, Division of Water Resource, Bulletin No. 118.1.

California Department of Water Resources, 1973, Evaluation of ground-water sources, south San Francisco Bay, Vol. 2, addition Fremont area study: State of California, Division of Water Resource, Bulletin No. 118-1.

California Department of Water Resources, 1974, Evaluation of ground-water resources, Livermore and Sunol Valleys: State of California, Division of Water Resource, Bulletin No. 118-2.

GENERAL REFERENCES (CONTINUED)

- California Department of Water Resources, 1975, Evaluation of ground-water resources, Sonoma County: Volume 1, Geology and hydrologic data. State of California, Division of Water Resource, Bulletin No. 118-4.
- Croft, M. G., 1972, Subsurface geology of late Tertiary and Quaternary water bearing deposits of the southern part of the San Joaquin Valley, California: U.S. Geol. Survey Water-Supply Paper No. 1999-H.
- Davidson, E. S., 1971, Facies distribution and hydrology of intermountain basin fill, Safford Basin, Arizona: in short papers in the geologic and hydrologic sciences, Articles 147-292, U.S. Geol. Survey Prof. Paper No. 424-C.
- Davidson, E. S., 1979, Summary Appraisals of the nation's ground-water resources - lower Colorado region: U. S. Geol. Survey Prof. Paper No. 813-R.
- Dent, O. F., 1966, Ground-water storage and use in Texas: Proceedings of 4th West Texas Water Conference, Texas Technological College.
- Dolcini, A. J., 1957, Santa Ana River Investigation: State of California, Division of Water Resource, Division of Resource Planning, Bulletin No. 15.
- Eakin, T. E., 1966, A regional interbasin ground-water system in the White River area, southeastern Nevada: Nevada Department of Conservation and Natural Resources, Water Resource Bulletin No. 33.
- Foxworthy, B. L., 1979, Summary appraisals of the nation's ground-water resources - Pacific-Northwest region: U. S. Geol. Survey Prof. Paper No. 813-S.
- Frank, J. F., and Johnson, N. A., 1970, Selected ground-water data in the Eugene-Springfield area, southern Willamette Valley, Oregon: State of Oregon with coop. United States Forest Service, Ground-Water Report No. 14.
- Glancy, P. A., 1968, Water resources appraisal of Mesquite - Ivanpah Valley area, Nevada and California: State of Nevada, Department of Conservation and Natural Resources, Reconnaissance Series Report No. 46.
- Haley, J. M., 1953, Santa Cruz and Monterey Counties: State of California, Division of Water Resources, State Water Resources Board, Bulletin No. 5.
- Havenor, K. C., 1968, Structure, stratigraphy, and hydrogeology of the northern Roswell artesian basin, Chaves County, New Mexico. New Mexico State Bureau of Mines and Mineral Resources, Circular No. 93.

GENERAL REFERENCES (CONTINUED)

- Kinney, E. E., 1968, A study of the Roswell artesian basin: Boswell Geological Society Publication.
- Mayer, J. D., and Newcomb, R. C., 1952, Geology and ground-water resources of the Swan Lake Valley area, Klamath County, Oregon: U. S. Geol. Survey coop. with Office of State Engineers of Oregon State.
- Molenaar, D. S., and Noble, J. B., 1970, Geology and related ground-water occurrence, southeastern Mason County, Washington: State of Washington, Department of Water Resource, Water-Supply Bulletin No. 29.
- Mower, R. W., and Feltis, R. D., 1968, Ground-Water hydrology of the Sevier Desert, Utah: U. S. Geol. Survey Water-Supply Paper No. 1854.
- Newton, V. C., Jr., 1969, Subsurface geology of the lower Columbia and Willamette Basins, Oregon: State of Oregon, Department of Geology and Mineral Industries, Oil and Gas Investigations No. 2.
- Noble, J. B., and Wallace, E. F., 1966, Geology and ground-water resources of Thurston County, Washington: Washington State Water-Supply Bulletin No. 10, Volume 2.
- Price, D., 1961, Records of wells, water levels and chemical quality of ground-water in the French Prairie - Mission bottom area, northern Willamette Valley Oregon: State of Oregon Ground-Water Report No. 1.
- Thomas, H. E., and Phoenix, D. A., 1976, Summary appraisals of the nation's ground-water resources - California region: U. S. Geol. Survey Prof. Paper No. 813-E.
- Thomasson, H. G., et. al., 1960, Geology, water resources and usable ground-water storage capacity of part of Solano County, California: U. S. Geol. Survey Water-Supply Paper No. 1464.
- West, S. W., Broadhurst, W. L., 1975, Summary appraisals of the nation's ground-water resources - Rio Grande region: U. S. Geol. Survey Prof. Paper No. 813-D.

Region 3. Columbia Lava Plateau

REGION 3 - COLUMBIA LAVA PLATEAU

INTRODUCTION

Region 3 is located in the Pacific Northwest area of the United States and lies between longitudes 112° West and 121° West and between latitudes 42° North and 48° North. The approximate land area is 130,000 square miles, bordered to the east and the west by high mountain ranges. The Cascade Range forms the western border, while the Selway-Bitterroot Mountains and the Continental Divide approximate the eastern border. The major population centers are widespread and include the following: Yakima, Moses Lake, Richland-Pasco-Kennewick and Wenatchee in central Washington; Bend, Pendleton, Baker, and Burns in central Oregon; and Lewiston, Boise, Twin Falls, and Pocatello in Idaho. Spokane, Washington, lies just outside the northeastern boundary. This region is contained entirely within the Columbia River drainage and is outlined in Figure 3-1.

The climate varies little throughout Region 3. The temperature ranges from a mean annual low of 5°C to a mean annual high of approximately 33°C. The greatest variation in the temperature can be attributed to the high desert areas and mountains of central and northeastern Oregon which include much land exceeding an elevation of 4,000 feet above mean sea level. A semi-arid, continental climate prevails over the region. Although the precipitation has extreme values from less than six inches to nearly 50 inches (mountainous ranges of northeastern Oregon and western Idaho), the range for the largest portion of Region 3 is from 10 inches to 20 inches annually. The majority of

the areas receive between nine inches to 14 inches of precipitation annually. The seasonal precipitation distribution is such that the majority of the rainfall occurs during the period from October to March, with up to 40 percent of the annual precipitation in November, December and January. The driest periods are from June to September and 10 percent or less of the annual precipitation occurs during July, August and September. The coincidence of the rainy season with the cooler, non-growing season is favorable to groundwater recharge. However, the seasonal distribution of the dry periods during peak growing season places a large demand on the ground-water reservoirs for crop irrigation.

Agriculture is the prime user of the region's fresh water resources, with food processing second to irrigation uses. Groundwater is by far the largest part of the region's freshwater resources, but its availability is not evenly distributed throughout the region. Although groundwater can be obtained nearly anywhere within the region, some localities have very low well yields and in other areas successful irrigation wells yield in excess of 1,500 gallons per minute.

Throughout the region the groundwater and surface water are inseparable parts of the hydrologic system. The good hydraulic interconnection between these two systems provides an excellent opportunity to maximize the beneficial use of the fresh water resources. However, prevailing water law addresses each of these two modes of water occurrence separately. As a result, many of the surface water resources are fully appropriated and the demand placed upon the region's principal ground-water reservoirs is expected to increase to meet the projected water supply needs.

GEOLOGIC FRAMEWORK

Throughout Region 3 two basic rock types are prevalent. These rock types are the various extrusive igneous rocks and several sedimentary deposits. Intrusive igneous rocks and metamorphic rock formations are less common and are grouped as Pre-Tertiary rocks. The oldest of these is the Precambrian Belt Super Group. These metamorphosed sedimentary rocks have limited local exposure along the northeastern region boundary. Younger Pre-Tertiary rocks are the early Mesozoic-aged (Brown and Newcomb 1962) highly metamorphosed, amphibolite facies rocks exposed in the Blue Mountain area of northeast Oregon (Hogenson 1964).

The next youngest of the Pre-Tertiary rocks are the late Mesozoic-aged (early Cretaceous) intrusive granites, granodiorites and some diorite rock types. The intrusive igneous rocks located in southwest Idaho are equivalent to the Idaho Batholith (Dion 1972). The south-central portion of the region also has similar granitic rocks as the core of the Owyhee Mountain Range (Ralston and Chapman 1969). Intrusive rock types of a mafic composition, such as diorites and norites, contact the Blue Mountain metamorphic rocks in northeastern Oregon. South of the Blue Mountain area at the headwaters of the Grande Ronde River, similar dioritic intrusive rocks occur as the Bald Mountain and Wallowa Mountain batholiths (Hampton and Brown 1964). A stratigraphic or age correlation was not available for these mafic intrusive igneous rocks. However, their stratigraphic position would place them somewhere in Cretaceous time. Throughout this region Pre-Tertiary rocks

are the basement rock group and are exposed in eastern Oregon, western Idaho and some localities along the southern boundary of the region.

In contrast to the limited exposure of the Pre-Tertiary rocks, the Tertiary and Quaternary sedimentary rocks are widespread. Sedimentary deposits in Region 3 do not have a great areal extent but exceed thicknesses of 1,000 feet in some localities and are most often associated with non-volcanic periods during late Tertiary time (Pliocene). The early Tertiary (Eocene) sediments of Region 3 are characterized by the Clarno Formation of eastern and central Oregon (Hogenson 1964). This formation consists of pyroclastic sediments, ash flow tuffs and thin felsitic to dacitic lava flows in the upper and westernmost strata. The lower sequences of the Clarno Formation contain quartz sandstone, micaceous shales and siltstones exposed in the eastern Oregon area. The John Day Formation (Oligocene), Madras Formation (Pliocene) and Mascall Formations are similar deposits of volcanic-derived sediments common to central Oregon (Robinson and Price 1962). In southern Idaho similar deposition was occurring in Late Tertiary time (Pliocene). These sedimentary deposits are closely associated with volcanism and include the Idaho Formation (Littleton and Crosthwaite 1957) Glens Ferry Formation in southwest Idaho (Dion 1972), some of the pyroclastic sediments in the lower Starlight Formation in southern Idaho (Crosthwaite 1974). Major Pliocene deposits in Washington include the Ellensburg Formation and the lower Ringold Formation (Foxworthy 1962; Deju and Fecht 1979).

The early Quaternary sedimentary deposits are often of glacial-fluvial origin including thick alluvial deposits in the Pasco Basin and

Boise Valley. These deposits can generally be considered Pliocene-Pleistocene in age and include the clay, silt and gravel of the Glenns Ferry Formation in southwest Idaho and the glacial fluvial outwash and flood deposits of the upper Ringold Formation in central Washington. Later Quaternary sedimentary deposits are mainly the Holocene glacial and alluvial deposits in river valleys and in the upland valleys.

The most extensive rock types throughout Region 3 are the Tertiary-aged silicic and basaltic lavas. The majority of volcanism took place during the middle to late Tertiary Period. The largest and best known volcanic rock type is the Miocene-aged Columbia River Basalt Group. These basalts cover over 50,000 square miles in Washington, Oregon, and Idaho. In south-central and southeastern Oregon early Tertiary (Eocene) volcanics are more silicic and are generally rhyodacitic to andesitic in composition. Several different volcanic rock formations are contained within this part of Oregon and many include pyroclastic deposits and ignimbrite sequences. The more common formations include the Clarno Formation, the John Day Formation, the Rattlesnake Formation, and the Danforth Formation. Late Tertiary volcanism was common to southern Idaho. The Pliocene-aged pyroclastic flows and welded rhyodacitic tuffs of the Walcott and Neeley Formations (Carr and Trimble 1963) and the Idavada Volcanics. Late Tertiary (Pliocene) basalts are found in southwest Idaho and include the Danbury Basalt and basalts of the Bruneau Formation. Early Quaternary basalt flows in southern Idaho belong to the Snake River Basalt and are generally considered to be younger than middle Pleistocene in age. The major Miocene- and Pleistocene-aged volcanic rock types are discussed in greater detail in the following subsections.

COLUMBIA RIVER BASALT GROUP

The Columbia River Basalt Group is a thick sequence of layered and intracanyon tholeiitic flood basalts consisting of five formations and 14 members which are shown on the stratigraphic chart of Figure 3-2. These basalts and the interbedded sedimentary rocks form a plano-convex, lenticular-shaped mass covering over 50,000 square miles in Washington, Oregon, and Idaho (Figure 3-3).

The basalts erupted from linear fissure systems in the eastern and southeastern areas of the Columbia Plateau. Recent potassium-argon age dating has determined that the Columbia River Basalt Group extends from Early Miocene to Late Miocene time. This period covers the time from approximately 23.5 million years before present to approximately 10.7 million years before present. Recent studies have shown that the rocks of the Columbia River Basalt Group were extruded primarily during a three-million-year time period occurring approximately between 16 million years before present to 13 million years before present (Swanson et al. 1979). These basalt flows occurred as a sequence of outpourings originating in the southeastern portion of Washington and northeastern portions of Oregon and flowed toward the northwest into the subsiding central portion of the Columbia Plateau region. The oldest flows of the Columbia River Basalt Group are generally the most extensive, while the youngest basalt flows are of limited extent and occur near the center of the basin. As a result, the basaltic outcrops generally become progressively older toward the higher elevations and periphery areas of the plateau region.

The Columbia River Basalt Group consists of only one sub-group; this group is known as the Yakima sub-group and consists of three

Series	Group	Sub-group	Formation	Member	K-Ar age (m. y.)		
M I O C E N E	Upper Miocene	COLUMBIA RIVER BASALT GROUP	YAKIMA BASALT SUBGROUP	Lower Monumental Member	6		
				erosional unconformity			
				Ice Harbor Member			
				basalt of Goose Island	8.5		
				basalt of Martindale	8.5		
				basalt of Basin City	8.5		
				erosional unconformity			
				Buford Member			
				Elephant Mountain Member	10.5		
				erosional unconformity			
				Pomona Member	12		
				erosional unconformity			
				Esquatzel Member			
				erosional unconformity			
				Weissenfels Ridge Member			
	basalt of Slippery Creek						
	basalt of Lewiston Orchards						
	Asotin Member						
	local erosional unconformity						
	Wilbur Creek Member						
	Umatilla Member						
	local erosional unconformity						
	Middle Miocene			Saddle Mountains Basalt	Wanapum	Priest Rapids Member	
						Roza Member	
						Frenchman Springs Member
					Basalt	Eckler Mountain Member	
						basalt of Shumaker Creek	
						basalt of Dodge	
						basalt of Robinette Mountain	
					Grande Ronde Basalt		14 - 16.5
		Picture Gorge Basalt					
			?			14.6-15.8	
		Lower Miocene	Imnaha Basalt				

REGIONAL COLUMBIA RIVER BASALT GROUP STRATIGRAPHIC NOMENCLATURE. (modified from Swanson, et, al., 1979)

OUTCROP EXTENT OF THE COLUMBIA RIVER
BASALT GROUP. (from Rockwell, 1979)

formations, Grande Ronde, Wanapum, and Saddle Mountain Basalts (Figure 3-2). The two deeper formations, the Imnaha Basalt and the Picture Gorge Basalt lie at great depths and outcrop in a few localities in northeastern and northcentral Oregon. The distribution of the formations within the Columbia River Basalt Group is given in Figure 3-4.

The Grande Ronde Basalt is the most widespread formation of the Yakima sub-group (Swanson et al. 1979). This unit covers virtually all of the Columbia Plateau in Washington and parts of the lower Columbia Valley in Oregon. This basalt is believed to be interlayered with the Picture Gorge Basalt in northcentral Oregon that rests conformably on the Imnaha Basalt in southeastern Washington. The Grande Ronde Basalt is generally separated from the disconformably overlying Wanapum Basalt by the Vantage member of the Ellensburg Formation in much of the western and central portions of the Columbia Plateau. This period of sedimentary deposition, which later thins to a zone of weathering in the eastern portion, suggests a major time break between the extrusion of the Grande Ronde Basalt and the beginning of the Wanapum Basalt extrusion.

The Wanapum Basalt consists of three members. Each member contains one or more flows which may be separated by sedimentary members of the Ellensburg Formation. The three basalt members, Priest Rapids, Rosa, and Frenchman Springs are shown in Figure 3-2 along with the names of the sedimentary interbeds commonly found separating them.

The Saddle Mountain Basalt is generally conformable with and overlies the Wanapum Basalt. Owing to periods of tectonism preceding

■ IMNAHA BASALT
 ■ PICTURE GORGE BASALT

GRANDE RONDE BASALT

WANAPUM BASALT

SADDLE MOUNTAIN BASALT

DISTRIBUTION OF FORMATIONS WITHIN THE
 COLUMBIA RIVER BASALT GROUP. (modified from
 Swanson and Wright, 1978)

deposition of the Saddle Mountain Basalt, some angular unconformities with the Wanapum Basalt have been formed in portions of the Columbia Plateau region. In addition, there were at least three intra-canyon flows that filled the ancestral Snake River Valleys during this time. The Yakima folds represent a time period which allowed thicker sequences of interbedded sediments to accumulate in the central portion of the plateau. These sedimentary interbeds are part of the Ellensburg Formation and are shown on Figure 3-2. The permeable nature of these materials allows for a substantial hydraulic interconnection for the groundwater in the youngest basalt flows of the Saddle Mountains with the unconfined or semi-confined groundwater in the overlying rock units. The extent of the Columbia River Basalt Group has been divided geographically into sub-basins based upon surface water drainage patterns (Figure 3-5).

SNAKE RIVER GROUP

The basaltic lava flows of the Snake River Group were extruded during early Quaternary time (Pleistocene). These basalts are present throughout most of southern Idaho and reach their western extent near the Mountain Home Plateau and south of the Boise Valley. Limited exposures of the Snake River Group are found in the northern parts of Owyhee County south of the Snake River near the towns of Murphy and Oreana. The eastern extension includes the northeast part of southern Idaho and covers an area north and east of Rexburg and St. Anthony (Figure 3-6). The basalt seldom occurs south of the Snake River. The most extensive portions of the Snake River Group form the Snake River Plain, covering approximately 9,600 square miles in a northeasterly direction from the town of Bliss, Idaho. The plain is bordered

MAJOR SUB-BASINS IN THE COLUMBIA PLATEAU

FIGURE 3-5

MAP OF SOUTHERN IDAHO SHOWING SNAKE RIVER
PLAIN AQUIFER. (modified from Crosthwaite, 1974)

FIGURE 3-6

to the northeast and the south by mountain ranges and alluvium-filled intermontane valleys.

The Snake River Group consists of extensive dark grey to black, vesicular olivine basalt flows that are sometimes considered to be a plagioclase-olivine basalt (Carr and Trimble 1963). These lavas were extruded along a southwest gradient which produced many flow structures and lava tubes within the basalt. The basalt unconformably overlies the Tertiary and Pre-Tertiary pyroclastic and sedimentary deposits. The underlying volcanic rock types are generally andesitic and contain several sedimentary interbeds which are also interbedded with the lower basalts of the Snake River Group. The various basalt formations and their associated interbeds comprising the Snake River Group were not thoroughly discussed in the available literature; therefore a stratigraphic section is not presented with this report.

HYDROGEOLOGIC FRAMEWORK

The general hydrogeologic framework follows the geology of Region 3. That is, there are three main hydrogeologic environments corresponding to the Columbia River Plateau, the Snake River Plateau, and the High Desert area of northeastern and central Oregon. Within these environments the major water-bearing strata are generally Middle Tertiary (Miocene) in age or younger. Minor water-bearing strata include the Holocene alluvial deposits, particularly along stream channels, and the alluvial fans along the mountain fronts. Often, the early Tertiary-(Paleocene, Eocene) aged, volcanic-derived sediments, common to central Oregon and parts of southwestern Idaho, yield small

amounts of groundwater. The three main hydrogeologic environments previously mentioned are of greatest interest and are further discussed in the following sections.

COLUMBIA PLATEAU GROUNDWATER RESERVOIR

The Miocene-aged Columbia River Basalt Group is the water-bearing rock type for this extensive ground-water reservoir that covers over 50,000 square miles within Region 3. Groundwater occurs within the vesicular tops of the various flow layers and to a limited extent occurs within the fractured colonnade portion of the flow. The numerous sedimentary interbeds also yield some groundwater. The total thickness of the Columbia River Basalt Group exceeds 10,000 feet in many locations, and in some locations is known to exist at depths over 19,000 feet below land surface. The geographic extent of the Columbia River Basalt Group is shown in Figure 3-3 (Rockwell 1979).

The major water-bearing formations are the Saddle Mountain, Wanapum and Grande Ronde Basalts. The deeper basalt flows, the Imnaha and Picture Gorge Basalt, are limited to a few outcrops in northeastern and northcentral Oregon. The Imnaha Formation occurs in a few localities in the Umatilla and Grande Ronde River valleys, in the lower reaches of Imnaha River and in the Snake River Canyon. The Picture Gorge Formation is limited to central and northcentral Oregon. Although these basalts are part of the Columbia River Group and possibly contain water-bearing strata, they are isolated from the remainder of the Columbia Plateau ground-water reservoir. Therefore, their hydrogeologic properties are not discussed here.

The Saddle Mountain, Wanapum and Grande Ronde Basalts are part of the continuous Columbia River Plateau ground-water reservoir which

contains a local, an intermediate, and possibly a regional ground-water flow system. The extent of each of the three main basalt flows is shown in Figure 3-4. The shallowest, local ground-water flow system contains unconfined aquifers in the overlying sediments and within the uppermost basalt flows. A local type of flow system is often of limited areal extent and is commonly contained entirely within the several local drainage basins of the Columbia River Plateau (Deju and Fecht 1979). The various topographic drainage basins and their associated sub-basins are shown in Figure 3-5. The hydrogeologic characteristics of the three main water-bearing basalt formations and their relationships with the topographical basins within the plateau are discussed in the following sections.

Saddle Mountain Basalt - The confined ground-water aquifers of the Saddle Mountain Basalt can generally be considered a local ground-water flow system. The flow paths are longer than in the overlying unconfined aquifers but generally the recharge and discharge boundaries are controlled by the local drainage basins. However, there is some inter-basin ground-water transfer between the Pasco Basin and both the Big Bend and Palouse/Snake Basins. The recharge to the Saddle Mountain Basalt aquifers is from direct infiltration of precipitation and stream runoff occurring in the Rattlesnake Hills, Yakima Ridge, Athanum Ridge and the Saddle Mountains (Rockwell 1979). Artificial recharge from irrigation occurs along the eastern and northeastern edges of the Saddle Mountain Basalts. The artificial recharge is a result of the Columbia Basin Irrigation Project including Scootney Reservoir, which is probably a major artificial recharge area. Recharge to overlying and underlying aquifers can occur locally where favorable

geologic and hydraulic head conditions exist. Although the degree of interconnection and interaquifer ground-water transfer is largely unknown, evidence indicates that it does exist.

The generalized ground-water movement is eastward from the natural recharge areas and in a more southerly direction from the artificial recharge areas. The ground-water movement is assumed to conform closely to the regional rock dip as the water travels toward the major discharge areas along the Columbia River between Richland and Wallula Gap. In this area, the Saddle Mountain Basalts are in direct contact with the Columbia River beneath Lake Wallula. Since all hydraulic heads for the Saddle Mountain Basalt aquifers are greater than the average Lake Wallula elevation of 317 feet above mean sea level, direct discharge to this lake is possible. Minor discharge is probable along the Yakima River west of Richland where the river elevation is between 335 to 381 feet above mean sea level. The Columbia River north of Umtanum Ridge may also be a point of minor discharge as the river intercepts southward-moving ground-water flow from the western portion of the Saddle Mountains (Deju and Fect 1979).

Wanapum and Upper Grande Ronde Basalt - The Wanapum and upper Grande Ronde Basalt aquifers can most likely be considered intermediate ground-water flow systems. However, the lower Grande Ronde Basalt may be part of the regional flow system. The Wanapum and Grande Ronde Basalt receive both interbasin recharge and recharge from outlying areas. Local recharge for the Wanapum Basalt is similar to that of the Saddle Mountain Basalts, particularly along the Saddle Mountain and Umtanum Ridge. The Grande Ronde Basalt receives local recharge from infiltration at outcrop areas along the northern flank of

Umtanum Ridge and within Sentinel Gap where the Columbia River is the probable source. Regional recharge to the Wanapum and Grande Ronde Basalts comes from both the eastern and western sides of the Columbia Plateau (Deju and Fect 1979).

Extensive outcrops in the northwest occur in the Yakima, upper Yakima and Kittitas Basins adjacent to the Cascade Range. A major portion of the regional recharge originates here from precipitation, infiltration, and stream flow losses along the Cascade foothills. The eastern interbasin or regional recharge is a result of interbasin groundwater flow from the Big Bend Basin and the Palouse/Snake Basin. The Wanapum and Grande Ronde Basalts also crop out east of Walla Walla, Washington, and in the Walla Walla River basin, but the recharge from this area probably does not move past Lake Wallula.

Wanapum and Grande Ronde Basalts outcrop in the Snake River Gorge upstream of Ice Harbor Dam and also along the fringe of the Columbia Plateau. The Snake River is likely an eastern discharge area for these basalts. A western discharge area is the Columbia River, possibly in Lake Wallula or further into the Columbia Gorge where these basalts may be in hydraulic connection with the river. This discharge could occur as a result of vertical leakage in areas structurally deformed or through direct contact between the Columbia River and the basalts (Deju and Fect 1979).

SNAKE RIVER PLAIN GROUNDWATER RESERVOIR

The Snake River Plain aquifer is composed primarily of basalts of the Snake River Group and covers approximately 9,500 square miles in southeastern Idaho. The Snake River Plain aquifer lies north of the

Snake River and extends in the northeast direction from the town of Bliss, Idaho, somewhat north and east of the Rexburg, St. Anthony area (Figure 3-6). In a 1969 estimate, this aquifer yielded approximately one million acre feet per year of water to irrigation wells (Crosthwaite 1974). An approximate 1975 estimate showed the ground-water use had increased to 1.57 million acre feet per year (1,400 million gallons per day) (Foxworthy 1979). The areal extent of the Snake River Plain Aquifer is shown in Figure 3-6.

The Snake River Plain Aquifer is composed of a series of vesicular basaltic lava flows including interflow beds containing pyroclastic and sedimentary rock types. Ground-water movement is mainly related to, and occurs within, the interflow zones where permeable openings range in size from cavernous lava tubes to the capillary openings in the sedimentary interbeds (Norvitch, Thomas and Madison 1969). The massive basalt comprising the core of each individual lava flow has few, if any, interconnected pore spaces and is therefore essentially impermeable. The permeable interflow zones are not completely separated by the dense core basalt but are interconnected along vertical joints, fault zones and in places where individual flows terminate. Also, feeder dikes may extend through large thicknesses of basalt and can extend laterally for miles. Individual dikes may terminate permeability channels in the flow rocks, or they may create additional permeability channels resulting from structural breakage owing to their emplacement. Thus, the Snake River Plain ground-water flow system is highly anisotropic and nonhomogeneous. Although the aquifer has been extensively studied and its general extent and properties are known, it is so large and thick, and contains such a variety of interrelated flows, that data

on the distribution of the basalt flows and interbedded sedimentary/pyroclastic deposits controlling the movement of groundwater have not been thoroughly evaluated.

Recharge to this aquifer is from precipitation infiltration and from the extensive stream flow losses occurring along the northern and northeastern edges. Approximately 6.5 million acre feet of water is recharged annually to this aquifer by seepage loss from the Snake River and its tributaries, by underflow from tributary valleys, by downward percolation of irrigation water and by precipitation on the plain (Crosthwaite 1974). Many streams originating in the high mountain ranges and uplands, which form the northeast boundary, lose their entire volume of flow to ground-water seepage as they flow across the Snake Plain. The northern side of the Snake River along this plain is essentially devoid of any inflowing surface streams.

Most natural discharge from the Snake River Plain Aquifer occurs from two groups of springs along the Snake River. The easternmost group extends from the mouth of the Black Foot River to a short distance below American Falls and accounts for approximately 28 percent of the total natural annual discharge or about 1.8 million acre feet per year (Norvich, Thomas and Madison 1969). The westernmost group extends from below Milner to King Hill and accounts for approximately 72 percent of the total annual natural discharge or about 4.7 million acre feet per year (Norvich, Thomas and Madison 1969). A third minor group of springs at the eastern end of Lake Walcott accounts for less than one percent of the total annual discharge.

Generally, the Snake River Plain Aquifer yields water to wells under water table conditions and in the amounts ranging from 100 gallons per minute to 1,200 gallons per minute. The well yields are

variable from location to location and are a result of the highly variable permeability. Therefore the transmissivity values vary throughout the individual lava flows of the Snake River Group. The water-bearing strata are generally close to the surface and well depths range from 200 feet to 1,000 feet below land surface and the majority of successful irrigation wells range between depths of 250 to 500 feet below land surface. Owing to the water table conditions, the static water level within these wells is generally low and ranges between 80 to 300 feet above the well bottom. Occasionally wells deeper than 700 feet have higher water levels. The highly variable water levels are caused by hydrostatic head variations within individual flow zones. Most often, the water levels are low and stand less than 150 feet above the well bottom.

HIGH DESERT GROUNDWATER RESERVOIR

The High Desert area includes the largest part of central and eastern Oregon. This area is largely undeveloped and very sparsely populated. The prime use of groundwater is for domestic and stock water and some irrigation in central Oregon. Generally, few crops are grown and only limited pasture areas are irrigated. The 1970 groundwater withdrawal estimate for this area was approximately 2.56×10^5 acre-feet per year (230 million gallons per day) (Foxworthy 1979). Much of this land area is near or exceeds an elevation of 4,000 feet above mean sea level. Therefore, increased ground-water withdrawals for crop production are not expected.

Geologically, this area does not contain the Columbia River Basalt Group or basalt of the Snake River Group. The only exception to this

may be the part of the High Desert area extending into the far southwestern edge of Idaho. The predominant rock types are extrusive silicic volcanic rocks, generally Middle to Late Tertiary in age (Miocene to Pliocene), and pyroclastic ash flow tuffs associated with them.

Early and Pre-Tertiary rocks are commonly found as sediments and some early pyroclastic flow deposits. Very limited data are available on the hydrogeologic characteristics of the various volcanic and volcanoclastic sediments of this area. The water-bearing strata capable of the highest yields are the volcanic aquifers. These rock types have a limited areal extent and therefore limited ground-water storage capacity. The aquifers in these volcanic rocks are often highly complicated by faults, dikes, flow structures, and pyroclastic interbeds. In some areas the more permeable lava flows lie above the local or regional ground-water level and do not store groundwater. The majority of ground-water storage in this region is most likely contained within the sedimentary deposits (Littleton and Crosthwaite 1957). The sedimentary rocks are generally the oldest and lie at excessive depth in many areas. Also, the fine-grained composition of these rocks greatly restricts their water yielding ability. Often, the water from sedimentary rocks in this area is of marginal quality. Local alluvial deposits in stream valleys and some alluvial fans have been successfully developed for groundwater, but are only local alluvial aquifers. Occasionally, a sand and gravel layer within the volcanoclastic rock types is tapped by a well and moderate to high yields are obtained. The highly variable nature of this type of aquifer is typical of the High Desert ground-water reservoir (Robinson 1971).

Throughout the High Desert area, recharge is from precipitation infiltration and stream flow losses in the mountainous areas. However, recharge is extremely limited because annual precipitation is low (6 to 13 inches) and evapotranspiration is high. Recharge seldom occurs in the more open central portions of this area. Discharge from the water-bearing strata takes place slowly to the scattered springs and to stream flow. Discharge by pumping is very minor but where concentrated, such as near small towns, ground-water level declines are considerable. Water level declines have been documented in the Prineville area of Crook County (Robinson and Price 1973) and Cow Valley area, Malheur County (Brown and Newcomb 1972). In other areas only a seasonal decline is noted.

The High Desert area is characterized by water-bearing strata of highly variable nature and limited data are available on the area's hydrogeology. For these reasons, the High Desert area is not considered to contain major regional aquifers and is not discussed further in this report.

MAJOR AQUIFERS

For the purpose of this study, a major aquifer is identified as an aquifer with significant areal extent that can sustain typical well yields of at least 50 gallons per minute throughout its extent. The major aquifers are determined to be either suitable or unsuitable for thermal energy storage and a discussion of each aquifer's evaluation is presented in the following sections. The previous sections of this chapter described the geologic and hydrogeologic framework and introduced the common aquifers of Region 3.

The Hydrogeologic Framework section described the general occurrence of groundwater and discussed many water-yielding rock formations regardless of their areal extent or yield characteristics. Table 3-1 provides a listing of the major aquifers in the region. The following sections of this chapter will discuss only those aquifers described in previous sections as major aquifers.

Specific data pertaining to each major aquifer's quantitative properties are tabulated and listed according to porosity group in Table 3-2. The qualitative geologic characteristics of each hydrogeologic environment are generalized and also presented in Table 3-2. The specific reference for which quantitative data is cited can be identified by checking the title of the numbered reference cited after each set of data.

AQUIFERS UNSUITABLE FOR ATES

The previous sections discussed the geologic and hydrogeologic framework for Region 3. The conclusion was reached that the region contained two major aquifers. The Columbia Plateau Aquifer and the Snake River Plain Aquifer were selected as the two regional aquifers. The remainder of Region 3 contains central and eastern Oregon and the western side of southern Idaho. These portions of Region 3 contain many aquifers and various water-bearing strata, but they are minor in comparison to the selected regional aquifers. Also, there is only limited data available on the hydrogeologic characteristics of rocks outside of the Columbia Plateau Aquifer and Snake River Plain Aquifer. Owing to the regional character of these two aquifers, they are the subject of further discussion and evaluation for ATES development.

All of the major aquifers of Region 3 have been evaluated according to the guidelines established in the Introduction. On the basis of this evaluation many of the aquifers have been judged as generally unsuitable for ATES. In most cases, site-specific studies are needed to more fully evaluate the ATES potential of each aquifer. The aquifers judged at this time to be unsuitable for ATES are discussed below, together with the justification for their elimination from further consideration. Figure 3-7 provides a listing of the major aquifers of Region 3 are considered unsuitable for ATES at this time.

AQUIFER	REASONS FOR UNSUITABLE RECOMMENDATIONS	COMMENTS
Columbia Plateau Aquifer	Fracture porosity and leaky aquifer conditions.	All aquifers with fracture porosities are considered unsuitable for A.T.E.S. at this time owing to the random and unpredictable volumes of stored water in these aquifers.
Snake River Plain Aquifer	Highly variable conditions and fracture porosity.	All aquifers with fracture porosities are considered unsuitable for A.T.E.S. at this time owing to the random and unpredictable volumes of stored water in these aquifers.

MAJOR AQUIFERS UNSUITABLE FOR A.T.E.S. IN REGION 3

FIGURE 3-7

COLUMBIA PLATEAU AQUIFER

Basalt of the Columbia River Group consists of Miocene-aged basaltic lava flows covering approximately 50,000 square miles in Washington, Oregon, and Idaho. The major water-bearing strata form confined aquifers, which have their greatest vertical and horizontal extent in central Washington. The regional aquifer lies beneath the Columbia Plateau of central Washington and is herein referred to as the Columbia Plateau Aquifer. This aquifer is contained predominantly within the boundaries of Washington State.

The characteristics of this aquifer and other data are shown in Table 3-1 at the end of this chapter. Upon reviewing this data and evaluating other hydrogeologic information, it was determined that the Columbia Plateau Aquifer is unsuitable for ATEs development. There are two major characteristics of this aquifer which contribute to its unsuitability for ATEs. First, the aquifer's ground-water occurrence is controlled largely by secondary porosity resulting from fractures and joints and occurring within the broken vesicular tops of individual basalt flows. Sedimentary interbeds also yield water and are often in hydraulic connection with the vesicular flow tops. Secondly, the fractures and joints also allow a certain degree of interconnection to occur between the various interflow zones resulting in leaky aquifer conditions. Although the vertical permeability of these fracture and joint systems is low, vertical movement of the groundwater is documented and in many areas is responsible for the recharge to lower aquifers. The other major characteristics of the basalt aquifers fit fairly well into the suitable category as outlined in this report's Introduction. The transmissivity values average near 20,000 gallons per day per foot and the porosity values are close to the proper range (Rockwell 1979).

Despite the overall acceptability of the quantitative data, the physical characteristics are dominant and determine the unsuitability of the Columbia Plateau basalt aquifers for ATES development. Further research and actual testing of an ATES facility may show that the desirable quantitative characteristics overshadow the undesirable physical properties of these basalt aquifers. However, the current data and evaluation guidelines used herein have shown this aquifer to be currently unsuitable for ATES development.

SNAKE RIVER PLAIN AQUIFER

The Snake River Plain Aquifer is a series of vesicular-olivine basalt flows and interrelated pyroclastic and sedimentary deposits of the Snake River Group which underlie the Snake River Plain north and northeast of Bliss, Idaho. This regional aquifer is approximately 9,500 square miles in areal extent and is the highest-yielding, water bearing sequence of rocks in Idaho. The water-table conditions of this highly permeable aquifer yield large amounts of water to heavily used irrigation wells. The Snake River Plain Aquifer lies entirely north of the Snake River and entirely within the boundaries of Idaho State.

The hydrogeologic properties and other available aquifer characteristics are shown in Table 3-2 of this chapter. Upon reviewing this data and other available information, the Snake River Plain Aquifer is considered unsuitable for ATES development. The deciding criteria are primarily qualitative owing to the unavailability of quantitative data. The basalts were extruded down-gradient, producing definite basalt flow layers and flow fronts which terminated when cooled, and then the

basalt flow front was ruptured from within by the still molten inter-lavas. This created complex flow structures and lava tubes within the flows. The resulting porosity is large and very randomly oriented. Later dike and fault action produced secondary porosities that are also undesirable for ATES aquifers. Also, the basalt flows are interbedded with pyroclastic flows and some welded ash flow tufts. These deposits further add to the high variability of the Snake River Plain aquifer. The highly vesicular and broken flow tops have very large transmissivity values and can be assumed to have high permeability. These conditions, along with the lava tubes previously mentioned, create large, natural pore velocities undesirable for an ATES aquifer.

Despite the lack of abundant quantitative data, which are available for the Columbia Plateau Aquifer, the qualitative geologic data are sufficient to determine the ATES potential of the Snake River Plain Aquifer. As stated in the previous paragraph, the aquifer is unsuitable for ATES development. Further research, such as the ground-water studies of the Idaho National Engineering Laboratory (INEL), will provide a more complete background for evaluating this aquifer and are likely to provide additional documentation for its unsuitability.

REGION'S ATES POTENTIAL

The potential for heat storage in the aquifers of Region 3 is very low. The two regional aquifers have been evaluated and rejected primarily on geologic considerations. The remaining water-bearing formations are in central and eastern Oregon and parts of Idaho south of the Snake River. These aquifers appear to be unsuitable because of their complex geology and absence of any continuous regional formations. Owing to the regional scope of this study, only the regional aquifers of Region 3 were considered for ATES potential, and only the most recent and available literature was reviewed. Site-specific information may possibly prove that the sub-regional aquifers have potential for ATES at particular localities. Upon further investigation, the sedimentary deposits in central Oregon and western Idaho may have local ATES potential. This may be particularly true for the Boise Valley area, which contains thick sedimentary sequences. The purpose of this regional study is to determine the aquifers with the greatest potential for ATES and should not preclude site-specific investigations.

REFERENCES CITED

- Brown, S. G., and Newcomb, R. C., 1962, Ground-water resources of Cow Valley Malheur County, Oregon: U. S. Geol. Survey Water-Supply Paper 16191-M, 38 p.
- Carr, W. J., and Trimble, D. E., 1963, Geology of the American Falls quadrangle, Idaho: U. S. Geol. Survey Bull. 1121-G, 44 p.
- Crosthwaite, E. G., 1974, A progress report on results of test-drilling and groundwater investigations of the Snake Plain Aquifer, south-eastern Idaho, part 3, Lake Walcott-Bonanza lake area: Idaho Dept. of Water Resources Water Inf. Bull. No. 38, 18 p.
- #015 Deju, R. A., and Fecht, K. R., 1979, Preliminary description of hydro-logic characteristics and contaminant transport potential of rocks in the Pasco Basin, south-central Washington: Rockwell Hanford Operations RHO-BWI-LD-20, Richland, Washington.
- Dion, N. P., 1972, Some effects of land-use changes on the shallow ground-water system in the Boise-Nampa area, Idaho: Idaho Dpt. of Water Administration Water Inf. Bull. No. 26, 46 p.
- Foxworthy, B. L., 1962, Geology and ground-water resources of the Ahtanum Valley, Yakima County, Washington: U. S. Geol. Survey Water-Supply Paper 1598, 100 p.
- Foxworthy, B. L., 1979, Summry appraisals of the Nations ground-water resources - Pacific Northwest region: U. S. Geol. Survey Prof. Paper 813-S, 37 p.
- Hampton, E. R. and Brown, S. G., 1964, Geology and ground-water resources of the Upper Grande Ronde River Basin Union County, Oregon: U. S. Geol. Survey Water-Supply Paper 1597, 98 p.
- Hogenson, G. M., 1964, Geology and ground-water of the Umatilla River Basin Oregon: U. S. Geol. Survey Water-Supply Paper 1620, 162 p.
- Littleton, R. T., and Crosthwaite, E. G., 1957, Ground-water geology of the Bruneau-grand View area, Owyhee County, Idaho: U. S. Geol. Survey Water-Supply Paper 1460-D.
- Mundorff, M. J., 1967, Groundwater in the vicinity of American Falls reservoir, Idaho: U. S. Geol. Survey Water-Supply Paper 1846, 58 p.
- #016 Norvitch, R. F., Thomas, C. A., and Madison, R. J., 1969, Artificial recharge to the Snake Plain aquifer in Idaho: an evaluation of potential and effect: Idaho Dept. of Recl. Water Inf. Bull. No. 12, 56 p., 13 fig., 3 tbl.

REFERENCES CITED (CONTINUED)

- Ralston, D. R. and Chapman, S. L. 1969, Ground-water resources of northern Owyhee County, Idaho: Idaho Dpt. of Reclamation Water Inf. Bull. No. 14, 85 p.
- Robinson, J. W. and Price, Don, 1963, Ground-water in the Prineville Area Crook County, Oregon: U. S. Geol. Survey Water-Supply Paper 1619-P, 49 p.
- #017 Robison, J. H., 1971, Hydrology of basalt aquifers in the Hermiston-Ordinance area, Umatilla and Morrow Counties Oregon: U. S. Geol. Survey Hydrol. Inv. Atlas, HA-387.
- Rockwell Hanford Operations, Basalt Waste Isolation Project, Annual Report - Fiscal Year 1979: Rockwell Hanford Operations Energy Systems Group, Richland, Washington, chapters II, III, and IV.
- Swanson, D. A., et al, 1979, Revisions in stratigraphic nomenclature of the Columbia River Basalt Group: U. S. Geol. Survey Bull. 1457-G, 59 p.
- Swanson, D. A., and Wright, T. L., 1978, Bedrock geology of the northern Columbia Plateau and adjacent areas; in the channeled Scabland, Baker, V. R., and Nummedal, D.: Office of Space Administration and National Aeronautics and Space Administration, 185 p.

GENERAL REFERENCES

The following references for Region 3 were reviewed, but are not cited in the report.

- Barker, R. A., 1979, Computer simulation and geohydrology of a basalt aquifer system in the Pullman-Moscow Basin, Washington and Idaho: State of Washington Dpt. Ecology Water-Supply Bull. No. 48, 119 p.
- Bingham, J. W. and Grolier, M. J., 1966, The Yakima Basalt and Ellensburg Formation of southcentral Washington: U. S. Geol. Survey Contribution to Stratigraphy, Bull. 1224-G, 15 p.
- Brott, C. A., Blackwell, P. D., and Mitchell, J. C., 1976, Geothermal investigations in Idaho, part 8, heatflow in the Snake River plain region, southern Idaho: Idaho Dpt. Water Resources Water Inf. Bull. 30, 195 p., 24 fig., 3 plates, 4 tbl.
- #018 Brown, J. C., 1979, Geology and water resources of Klickitat County: County: Washington State Dpt. Ecology Water-Supply Bull. No. 50, 413 p.
- #019 Castelin, P. M., 1976, A reconnaissance of the water resources of the the Clearwater Plateau, Nez Perce, Lewis and northern Idaho counties, Idaho: Idaho Dpt. of Water Resources Water Inf. Bull. No. 41, 46 p., 11 tbl., 7 fig.
- #020 Crosthwaite, E. G., Mundorff, M. J., and Walker, E. H., 1970, Ground-water aspects of the lower Henry's Fork region, eastern Idaho: U. S. Geol. Survey Water-Supply Paper 1879-C, 21 p.
- Davenport, R. E., 1970, Geology of the Rattlesnake and older ignimbrites in the Paulina Basin and adjacent area, central Oregon: Oregon State Univ. Ph.D. thesis, Geology.
- Garrett, A. A., 1968, Ground-water withdrawal in the Odessa area, Adams, Grant, and Lincoln counties, Washington: State of Washington Dpt. Water Resources Water Supply Bull. No. 31, 84 p.
- Gonthier, J. B., and Harris, D. D., 1977, Water resources of the Umatilla Indian Reservation, Oregon: U. S. Geol. Survey Water Resources Inv. 77-3, 111 p.
- Gregg, D. O., and Laird, L. B., 1975, A general outline of the water water resources of the Toppenish Creek basin, Yakima Indian Reservation, Washinton: U. S. Geol. Survey Open-File Report 75-19, 37 p.
- Griggs, Allan, B., 1976, The Columbia River Basalt Group in the Spokane Quadrangle, Washington, Idaho and Montana: U. S. Geol. Survey Bulletin 1413, 39 p.

GENERAL REFERENCES (CONTINUED)

- Leonard, A. R., 1970, Ground-water resources in Harney Valley, Harney County, Oregon: Oregon State Engineer Ground-Water Report No. 16, 85 p.
- Leonard, A. R., and Harris, A. B., 1974, Groundwater in selected areas in the Klamath Basin, Oregon: State of Oregon, Oregon State Engineer, Groundwater Report No. 21, 104 p.
- Luzier, J. E., and Skrivan, J. A., 1975, Digital-simulation and projection of water-level declines in basalt aquifers of the Odessa-Lind area, east-central Washington: U. S. Geol. Survey Water-Supply Paper 2036, 48 p.
- #021 Luzier, J. E., and Burt, R. J., 1974, Hydrology of basalt aquifers and and depletion of groundwater in east-central Washington: State of Washington Dpt. Ecology Water-Supply Bulletin No. 33, 53 p.
- Lystrom, D. J., Nees, W. L., and Hampton, E. R., 1967, Groundwater of Baker Valley, Baker County, Oregon: U. S. Geol. Survey Hydrol. Inv. Atlas HA-242.
- MacNish, R. D., and Barker, R. A., 1976, Digital simulation of a basalt aquifer system, Walla Walla River Basin, Washington and Oregon: State of Washington Dpt. Ecology Water Supply Bull. No. 44, 51 p.
- #022 Maddox, G. E., and Schalla, Ronald, 1979, A preliminary conceptual model of the Columbia Plateau Region, Washington: Rockwell Handord Operations RHO-BWI-C-51, Richland, Washington.
- Mitchell, John C., 1976, Geochemistry and geologic setting of the thermal and mineral waters of the Blackfoot Reservoir area Caribou County, Idaho: Idaho Dept. of Water Resources Water Inf. Bull. No. 30, part 6, 47 p.
- Mitchell, John C., 1976, Geochemistry and geologic setting of the thermal waters of the Camas Prairie area, Blaine and Camas Counties, Idaho: Idaho Dept. of Water Resources Water Inf. Bull. No. 30, part 7, 44 p.
- Mundorff, M. J., 1967, Groundwater in the vicinity of American Falls reservoir, Idaho: U. S. Geol. Survey Water-Supply Paper 1846, 58 p.
- Newcomb, R. c., 1961-A, Storage of groundwater behind sub-surface dams in the Columbia River Basalt Washington, Oregon, and Idaho: U. S. Geol. Survey Prof. Paper 383-A, 15 p.
- Newcomb, R. C., 1961-B, Groundwater in the western part of Cow Creek and Soldier Creek grazing units Malheur County, Oregon: U. S. Geol. Survey Water-Supply Paper 1475-E, 13 p.

GENERAL REFERENCES (CONTINUED)

- Newcomb, R. C., 1969, Effect of tectonic structure on the occurrence of groundwater in the basalt of the Columbia River Group of the Dalles area Oregon and Washington: U. S. Geol. Survey Prof. Paper 383-C, 33 p.
- #023 Newcomb, R. C., 1972, Quality of the groundwater in basalt of the Columbia River Group, Washington, Oregon, and Idaho: U. S. Geol. Survey Water-Supply Paper 1999-N, 71 p.
- Pearson, H. E., 1973, Test-observation well near Paterson, Washington; description and preliminary results: U. S. Geol. Survey Water Resource Inv. 9-73, 23 p.
- Pearson, H. E., 1977, Test-well drilling in the upper Status Creek basin, Yakima Indian Reservation, Washington: U. S. Geol. Survey Open-File Report 77-4455, 14 p.
- Price, Don, 1967, Ground-water reconnaissance in the Burnt River Valley area, Oregon: U. S. Geol. Survey-Water Supply Paper 1839-I, 27 p.
- Sammel, E. A., 1980, Hydrogeologic appraisal of the Kalamath Falls geothermal area, Oregon: U. S. Geol. Survey Prof. Paper 1044-G, 45 p.
- Sisco, H. G., 1974, Groundwater levels and well records for current observation wells in Idaho, 1922-73, parts A, B, and C,: U. S. Geol. Survey and Idaho Dpt. Water Resources Basic-Data Release.
- Skibitzke, H. E., and Costa, J. A., 1962, The ground-water flow system in the Snake River Plain, Idaho - an idealized analysis: U. S. Geol. Survey Water Supply Paper 1536-D, 67 p.
- #024 Tanaka, H. H., Hansen, A. J., Jr., and Skrivan, J. A., 1974, Digital-model study of ground-water hydrology, Columbia Basin irrigation project area, Washington: State of Washington Dpt. Ecology Water-Supply Bull. No. 40, 60 p.
- U. S. Geological Survey, 1975, Water resources of the Toppenish Creek basin, Yakima Indian Reservation, Washington: U. S. Geol. Survey, Water Resources Inv. 42-74, 144 p.
- Van Denburgh, A. S., and Santos, J. F., 1965, Groundwater in Washington its chemical and physical Quality: State of Washington Dpt. Conservation, Div. Water Resources Water-Supply Bull. No. 24, 93 p.
- #025 Walker, E. H., et. al., 1970, The Raft River basin, Idaho-Utah as of 1966: a reappraisal of the water resources and effects of groundwater development: Idaho Dpt. Water Administration Water Inf. Bull. No. 19, 93 p., 23 figs., 11 tpls.

GENERAL REFERENCES (CONTINUED)

- Walker, E. H. and Sisco, H. G., 1964, Groundwater in the Midvale and Council areas upper Weiser River basin, Idaho: U. S. Geol. Survey Water-Supply Paper 1779-Q, 25 p.
- Walters, K. L., and Glancy, P. A., 1969, Reconnaissance of geology and of ground-water occurrence in Whitman County, Washington: State of Washington Dpt. Water Resources Water-Supply Bull. No. 26, 167 p.
- Washington Department of Ecology, 1975, Geology, groundwater and water quality of part of southern Spokane County, Washington: Water Resources Inf. System Technical Bull. No. 15, 145 p.

Region 4. Colorado Plateau

REGION 4 - COLORADO PLATEAU

INTRODUCTION

The Colorado Plateau region includes the area drained by the Colorado River and its tributaries upstream from Lee Ferry, Arizona, and the area of the Great Divide Basin, a closed basin in Wyoming (Price and Arrow 1974). The region covers approximately 113,500 square miles in the northern parts of Arizona and New Mexico, the southern portion of Wyoming, the eastern part of Utah and the western part of Colorado (Fenneman et al. 1946).

The Colorado Plateau region is characterized by high rugged mountains, broad basins and highly dissected plateaus. The majority of the region drains into the Colorado River or its major tributaries, the Green, San Juan, and Gunnison Rivers, whose headwaters originate in the Southern and Central Rocky Mountains.

GEOLOGIC FRAMEWORK

Lithologic units exposed within the Colorado Plateau region range in age from Precambrian to Recent. Generally, the Precambrian older plutonic and metamorphic rocks form the basement complexes and are exposed in the adjacent mountain ranges from uplifting, faulting, and erosion. The basement complex underlies the basin areas at depths ranging from 1,000 to 10,000 feet.

Overlying the basement complex are flat-lying to gently folded sedimentary rocks of Mesozoic Age. Complex intertonguing and rapid facies changes are prevalent within this group. Regional uplift beginning in Late Cretaceous time formed the structural basins in which the more recent (Quaternary Age) sediments are deposited.

HYDROLOGIC FRAMEWORK

The major aquifers in this region occur in both the consolidated Mesozoic sediments and the more recent alluvial deposits (Figure 4-1). A list of the major aquifers is provided in Table 4-1. The principal occurrence of water in the Mesozoic sediments is within sandstone beds. Generally, these are associated with the Coconino, Navajo, Dakota, and Entrada Sandstones (Cooley 1969). The aquifers within these formations are composed of beds of sandstone between nearly impermeable strata of siltstone and mudstone. The siltstone and mudstone layers act as aquicludes and confine the water , under artesian pressure in much of the area of the major structural basins. For the most part, the aquifers in the fine-grained consolidated sedimentary rocks do not transmit water rapidly. Yields from wells are generally less than 25 gallons per minute and therefore do not meet the minimum yield requirement (50 gallons per minute) for ATEs (Price and Arrow 1974). Well yields are substantially higher where the sandstones are fractured. The increased well yields are owing to the secondary porosities in the fractured rocks. There are also aquifers associated with Mesozoic carbonate and volcanic rocks. These aquifers also have secondary porosities.

The alluvial deposits generally yield small quantities of groundwater to wells except where the deposits are thick and occur along principal streams. Only five percent of the estimated maximum recoverable water in storage occurs in unconsolidated deposits within this region (Price and Arrow 1974). Wells that yield more than 50 gallons per minute generally occur only along reaches of larger streams and in small, widely scattered, alluvium-filled basins. Owing to the rapid

OUTLINE OF REGION 4 WITH THE MAJOR AQUIFERS

FIGURE 4-1

facies changes associated with the alluvial deposits, the sand and gravel layers are not widespread and the alluvial aquifers are sub-regional in their extent.

Total dissolved solids both in alluvial and bedrock aquifers within the area varied from less than 350 milligrams per liter in the southern portion to between 500 and 10,000 milligrams per liter in the northern portion.

MAJOR AQUIFERS

For the purpose of this study, a major aquifer is identified as an aquifer with significant areal extent that can sustain typical well yields of at least 50 gallons per minute throughout its extent. The major aquifers are determined to be either suitable or unsuitable for thermal energy storage and a discussion of each aquifer's evaluation is presented in the following sections. The previous sections of this chapter described the geologic and hydrogeologic framework of Region 4.

The Hydrogeologic Framework section described the general occurrence of groundwater and discussed a few of the water-yielding rock formations regardless of their areal extent or yield characteristics. Table 4-1 provides a listing of the major aquifers in the region.

Specific data pertaining to each major aquifer's quantitative properties are tabulated and listed according to porosity group in Table 4-2. The qualitative geologic characteristics of each hydrogeologic environment are generalized and also presented in Table 4-2. The specific reference for which quantitative data is cited can be identified by checking the title of the numbered reference cited after each set of data.

AQUIFERS UNSUITABLE FOR ATES

All of the major aquifers of Region 4 have been evaluated according to the guidelines established in the Introduction. On the basis of this evaluation many of the aquifers have been judged as generally unsuitable for ATES. In most cases, site-specific studies are needed to more fully evaluate the ATES potential of each aquifer. The aquifers judged at this time to be unsuitable for ATES are discussed below, together with the justification for their elimination from further consideration. Figure 4-2 provides a listing of the major aquifers in Region 4 now considered to be unsuitable for ATES.

Within the region, aquifers are found in either unconsolidated sediments of alluvial basins or consolidated flat-lying sandstones, carbonates and volcanic rocks of Mesozoic age. Generally, in both hydrologic environments no aquifers were found at this time that would be considered suitable for ATES. Site-specific studies may identify local areas where the aquifers may be suitable for ATES.

ALLUVIUM

As established in the Hydrogeologic Framework section of this chapter, the sand and gravel aquifers associated with alluvial deposits of Recent age generally yield small quantities of water except where the deposits are thick and occur along principal streams. Wells that yield more than 50 gallons per minute generally occur only along reaches of larger streams and in small, widely scattered, alluvium-filled basins.

The sedimentary depositional environment associated with rivers and streams provides for rapid facies changes. As a result of rapid

AQUIFERS	REASONS FOR UNSUITABLE RECOMMENDATIONS	COMMENTS
Alluvium	Rapid facies changes make the hydrologic conditions vary from place to place; therefore aquifers are sub-regional in extent. Alluvium, in general, yields less than 50 gpm.	Site-specific studies may provide information that proves an alluvial aquifer is suitable for A.T.E.S. at a particular location.
Mesozoic Rocks -tight sandstones -carbonates -volcanics	Fracture Porosity	All aquifers with fracture porosities are considered unsuitable for A.T.E.S. at this time owing to the random and unpredictable volumes of stored water in these aquifers.

MAJOR AQUIFERS UNSUITABLE FOR A.T.E.S. IN REGION 4

facies changes, the sand and gravel aquifers are generally not widespread and hydrogeologic conditions may change markedly over the extent of the aquifer. An alluvial aquifer may be confined in some areas and unconfined in other areas; there may be variable hydrologic gradients and variable aquifer thicknesses.

Site-specific studies may establish that alluvial sands and gravels at a particular location are suitable for ATEs. However, the regional scope of this study dictates that, in general, these sub-regional aquifers should be eliminated from further consideration.

CONSOLIDATED MESOZOIC ROCKS

Aquifers occurring within the Mesozoic rocks generally yield less than 25 gallons per minute throughout most of the region. Where well yields are greater than 50 gallons per minute, it is usually owing to secondary porosity (i.e. fractures, caverns, solution cavities, etc.) associated with the carbonate and volcanic rocks, and sandstones. The massive sandstone formations in the region are generally tight and yield the minimum requirement of 50 gallons per minute only in the area where the sandstones are highly fractured.

A good example of the increased yields from secondary porosities is the Dry Lake Basin area. The area is described briefly by Mann (1976). The basin is essentially a folded, dome-shaped structure occurring between Snowflake and Shumay, Navajo County, Arizona. This domed area has approximately 250 feet of actual closure with potentiometric head about 150 feet above the aquifer. The Coconino Sandstone in this area is confined above by siltstone strata (Moenkopi

Formation) and below by a thick-bedded sequence of sedimentary and volcanic rocks. Well yields within the area varied from 500 to 2,500 gallons per minute, which is significantly higher than yields in any of the major aquifers throughout that region. These higher yields are associated with secondary porosity from the folding and subsequent fracturing of the sandstone.

Generally, aquifers in the consolidated rocks of the region may be eliminated from consideration for ATES development owing to the low well yields (less than 25 gallons per minute). In the areas where the bedrock aquifers do yield greater than 50 gallons per minute, the aquifers are unsuitable for ATES development because the increased yields are a result of structurally controlled fracture systems, or solution cavities in the carbonates. As established in the aquifer evaluation guidelines of this report, aquifers associated with secondary porosities are considered undesirable for ATES because of the somewhat random and unpredictable volumes of stored water in these aquifers. Therefore, all of the fracture porosity aquifers are eliminated from further consideration for ATES.

REGION'S ATES POTENTIAL

At this time none of the aquifers identified in Region 4 are considered regionally suitable for ATES. The aquifers of Region 4 have been categorized into two major groups: 1) the aquifers associated with alluvial deposits; and 2) the aquifers associated with the consolidated Mesozoic rocks. The alluvial aquifers were eliminated from consideration for ATES potential owing to their sub-regional extent. The aquifers associated with the Mesozoic rocks were eliminated from consideration for ATES owing to their secondary porosities.

The regional scope of this study dictates that only the regional aquifers of Region 4 were considered for ATES potential, and only the most recent and available literature was reviewed. Site-specific information may possibly identify particular localities where an aquifer in Region 4 may be suitable for ATES. The purpose of this regional study is to identify the major aquifers of a region and to evaluate their general potential for ATES. The study should not preclude site-specific investigations.

REFERENCES CITED

Cooley, M. E., 1969, Regional hydrogeology of the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah: U. S. Geol. Survey Prof. Paper No. 521-A.

Fenneman, N. M., et. al., 1946, Physical divisions of the United States: U. S. Geol. Survey map, scale 1:7,000,000.

#026 Mann, L. J., 1976, Ground-water resources and water use in southern Navajo County, Arizona: U. S. Geol. Survey. Arizona Water Commission Bulletin No. 10, 106 p.

Price, D., and Arrow, T., 1974, Summary appraisals of the nation's ground-water resources - upper Colorado region: U. S. Geol. Survey Prof. Paper No. 813-C.

GENERAL REFERENCES

- Babcock, H. M., 1975, Annual report on ground-water in Arizona with emphasis on Gila Bend basin, McMullun Valley, and southeastern part of Harquahala Plain-spring 1973 to spring 1974: District Chief of U. S. Geol. Survey in Arizona, Arizona Commission Bulletin No. 9.
- Berry, D. W., 1960, Geology and ground-water resources of the Rawl-ings area, Carbon County, Wyoming: U. S. Geol. Survey Water-Supply Paper No. 1458.
- Gregany, H. E., 1916, The Navajo County, geographic and hydrologic reconnaissance of parts of Arizona, New Mexico, and Utah: U. S. Geol. Survey Water-Supply Paper No. 380.
- Iorns, W. V., et. al., 1965, Water resources of the upper Colorado River Basin - a technical report: U. S. Geol. Survey Prof. Paper No. 441.
- Irwin, J. H., 1966, Geology and availability of ground-water on the Ute Mountain Indian Reservation, Colorado and New Mexico: U. S. Geol. Survey Water-Supply Paper No. 1576-G.
- Lohman, S. W., 1965, Geology and artesian water supply, Grand Junc-tion area, Colorado: U. S. Geol. Survey Prof. Paper No. 451.
- Pettyjohn, W. A., 1979, A ground-water quality Atlas of the United States: prepared under research section of the National Water Well Association for the National Demonstration Water Project.

Region 5. High Plains

REGION 5 - HIGH PLAINS

INTRODUCTION

Region 5 encompasses the area of the mid-continent extending from southern South Dakota to the Texas Panhandle. The boundary of the region is roughly equivalent to the areal extent of the Ogallala Formation of Pliocene age (Figure 5-1).

The climate varies from semi-arid throughout most of the region to humid in the eastern portions of the region in Kansas and Nebraska. The average annual precipitation is consistently from 12 to 20 inches of precipitation per year throughout most of the region but increases to 30 inches of precipitation per year in the eastern portions of the region (Geraghty et al. 1973). The aquifers in Region 5 are recharged by infiltration of precipitation; however, most of the precipitation is lost through evapotranspiration and runoff.

Throughout Region 5 tremendous withdrawals of groundwater, principally from the Ogallala Formation, are used for irrigation. Other uses of groundwater resources are municipal, domestic, and livestock supplies. Owing to the importance of groundwater to the growth and development of the region, there is a concern that the water levels of the aquifers in the region may decline in response to overdevelopment (Hosek 1975).

The surficial aquifers, of Quaternary and Tertiary age, generally are not reported to have salinity problems. However, in the Cretaceous sandstones (such as the Dakota Sandstone) and older sandstones the degree of salinity often makes the groundwater unsuitable for most uses.

In the portion of Region 5 that lies in Oklahoma and Texas, the saline aquifers are commonly used for oil field brine disposal.

GEOLOGIC FRAMEWORK

The geologic framework of the High Plains is basically uniform over the extent of Region 5. The unconsolidated deposits of Quaternary and Tertiary age are the same throughout the region. The marine sedimentary rocks of Cretaceous age and older vary somewhat from the northern portion of the High Plains to the southern portion of the High Plains. Figures 5-2 and 5-3 provide the names and ages of the geologic formations, with their water-bearing properties, for the geologic units found in the High Plains.

UNCONSOLIDATED DEPOSITS OF RECENT AND PLEISTOCENE AGE

Unconsolidated deposits of Recent and Pleistocene age blanket the High Plains. The deposits vary in character depending upon the depositional environment in which they were laid down. The principal types of deposits of Recent and Pleistocene age are alluvium, dunes, and loess. The following discussion outlines the general occurrence and geology of the three major types of Quaternary deposits.

Alluvium

The alluvium of Recent and Pleistocene age may be found along the courses of present-day rivers and streams. The alluvium of Recent age consists of silt and clay flood plain deposits and sands and gravels associated with channels and point bars. Therefore, there are rapid

SYSTEM	SERIES	GEOLOGIC UNIT		THICKNESS (FT.)	PHYSICAL CHARACTER	WATER SUPPLY
QUATERNARY	Holocene and Pleistocene	Alluvium		0 to 75	Unconsolidated gravel, sand, silt, and clay both intermixed and as alternating layers.	Locally may yield as much as 2,000 gpm of fair to poor quality water in the valleys of the North and South forks of the Republican River and the Arikaree River. However, yields of less than 500 gpm are more common.
		Dune sand		0 to 100	Tan unconsolidated gravel very fine to coarse quartz sand; wind-deposits.	Generally lies above the water table and, hence, yield no water to wells. May yield amounts adequate for stock and domestic purposes where saturated. The dunes are catchment areas for recharge from precipitation, owing to the high permeability of the sand.
	Pleistocene	Unconformity				
		Peoria Loess		0 to 120	Yellowish-gray silt, fine sand, and clay containing scattered calcareous concretions; wind-deposits.	Lies above the water table and, hence, yields no water to wells. Many intermittent lakes form on surface.
		Unconformity				
		Undifferentiated deposits.		0 to 40	Clay, silt, sand, and gravel. Caliche stringers throughout. Some volcanic ash, colluvium, and slope wash.	Generally drained. Yields as much as 20 gpm of water to domestic and stock wells in some areas.
		Unconformity				
TERTIARY	Pliocene	Ogallala Formation		0 to 460	Poorly sorted gravel, sand, silt, and clay containing beds of limy sandstone, opaline material, and volcanic ash; caliche beds at top; stream-deposited.	Principal aquifer. Yields as much as 3,000 gpm of good quality water to irrigation wells. Supplies stock, domestic, and public-supply wells throughout most of the area.
	Oligocene	Unconformity				
		White River Group	Brule Formation	0 to 255	Siltstone and clayey silt.	The upper part may yield as much as 500 gpm of water to wells from fractured zones or zones of reworked siltstone pebbles.
			Chadron Formation	0 to 235	Clay, claystone, silty clay, sandstone. May contain lenses of permeable quartz sand gravel near the contact with the Pierre Shale.	The lower part may yield as much as 500 gpm of water to wells from lenses of permeable sand and gravel.
CRETACEOUS	Upper Cretaceous	Pierre Shale		0 to 40, 600	Gray to black marine shale containing gypsum, bentonite, and calcareous concretions; weathered zone of yellow clay usually present at top.	Yields as much as 15 gpm of water to wells from silt in the upper weathered zone. Forms the lower confining layer for water in overlying unconsolidated deposits.
		Niobrara Formation	Smoky Hill Marl Member	200 to 700	Dark to light gray chalky shale; contains gypsum and chalky limestone; weathers to orange or light yellow.	Yields as much 300 gpm. However, most wells yield only enough water for stock. The water is obtained from weathered zones, and is of poor chemical quality. Yields no water in some areas.
			Fort Hays Limestone Formation	30 to 110	White chalky limestone; contains thin beds of chalky shale.	Yields as much as 15 gpm of water to stock wells near outcrop areas.
		Carlisle Shale	Codell Sandstone Member	30 to 50	Chiefly calcareous sandy shale; contains beds of very fine-grained calcareous sandstone.	Yield as much as 15 gpm of water to domestic and stock wells.
			Blue Hill Shale Member	50 to 150	Black noncalcareous shale.	Not known to yield water to wells in the report area.
		Greenhorn Limestone		40 to 175	Gray to black interbedded limestone and shale. Lower parts of unit contains thin platy petroliferous limestone beds and thin crystalline limestone beds.	Low-permeability confining bed; acts as a barrier to vertical movement of ground water. Not known to yield water to wells in the report area.
		Graneros Shale		60 to 170	Black fissile fossiliferous shale; contains stringers of gypsum and bentonite, and thin crystalline limestone beds.	Low permeability confining bed; acts as a barrier to vertical movement of ground water. Not known to yield water to wells in the report area.
	Lower Cretaceous	Dakota Sandstone		200 to 550	Clay to brown sandstone interbedded with sandy shale, siltstone, and clay. Sandstone beds are cross-bedded, and in some places contain limonite and coal. The beds vary from quartzitic to friable and locally are fractured.	Minor source of water for domestic and stock wells in southern part of the area. Brackish and saline in most of the area. Yield as much as 20 gpm.

GEOLOGIC FORMATIONS AND THEIR WATER-BEARING PROPERTIES NORTHERN HIGH PLAINS

(adapted from Hofstra, Major, and Lucky, 1972)
FIGURE 5-2

SYSTEM	SERIES	SUBSERIES	STAGE	GEOLOGIC UNIT	THICKNESS IN FEET	PHYSICAL CHARACTER	WATER SUPPLY
NEOGENE	Pleistocene	Upper (?) Pleistocene	Recent Wisconsinan Sangamonian Illinoian	Undifferentiated eolian and alluvium deposits.	0 to 270 ±	Soil, loess, dune sand, alluvium on surface. Clay, silt, sand, and gravel in subsurface.	Where saturated, known to yield 750 gpm from sand and gravel; higher yields may be possible. (Most deposits lie above water table and yield no water to wells.)
		Lower Pleistocene(?)	Yarmouthian Kansan Aftonian Nebraskan	Undifferentiated alluvial deposits.	0 to 300 ±	Coarse sand and gravel deposits in channel fill; silt, fine sand, and clay in backwater and inter-stream deposits.	Wells screened only in Lower Pleistocene (?) deposits yield up to 2,000 gpm.
	Pleistocene			Ogallala Formation	0 to 200 ±	Silt, clay, sand, and gravel. (Sand and gravel lenses may contain large amounts of inter-bedded silt and clay.)	Yields up to 1,000 gpm obtained in areas of coarse channel-fill deposits
CRETACEOUS	Lower	(disconformity)		Dakota Formation (L. ? Cret)	0 to 135 ±	Fine to medium grained sandstone with shale beds.	Yields small supplies of water for stock and domestic wells. Yields water to multiple-aquifer irrigation wells.
				Kiowa Shale	0 to 150 ±	Gray to black silty shale; contains some thin sandstone beds.	Yields little or no water to wells.
				Cheyenne Sandstone	0 to 120 ±	White to yellow fine to coarse quartzose	Yields up to 500 gpm possible. Yields water to multiple-aquifer irrigation wells.
TRIASSIC(?)	Upper	(disconformity)		Dockum Group (undivided in Kansas)	0 to 130 ±	Fine to medium gravel, quartzose sandstone. Contains red sandstone and siltstone.	Yields up to 1,000 gpm reported. Yields water to multiple-aquifer wells
				Big Basin Formation	100 +	Dark-red mudstone and orange-red siltstone beds.	No information available.

GEOLOGIC FORMATIONS AND THEIR WATER-BEARING PROPERTIES
SOUTHERN HIGH PLAINS (adapted from Fader, et. al., 1964)

facies changes in these deposits over short distances. The alluvium of Pleistocene age consists primarily of sand and gravels that were deposited on outwash plains by meltwater streams from the continental glaciers. This alluvium is typically exposed in terraces above the flood plains of present-day streams. The sands and gravels of Pleistocene age are generally more widespread, with less facies changes, than alluvium of Recent age.

Dunes

Dune deposits may be found on the upland surfaces throughout Region 5. The High Plains dunes are generally composed of very well-sorted, fine-grained quartz sand; however, in some areas coarse-grained sands may be found. Basically, the dune deposits are characteristically homogeneous. On the plains of north-central Nebraska and south-central South Dakota, the surficial deposits are predominantly dune sand and the area is commonly referred to as the sand hills (Engberg and Spalding 1978).

Loess

The upland surfaces of Region 5 are most often blanketed by loess which may be up to 120 feet thick (Hofstra, Major and Lucky 1972). The loess was deposited by winds during Pleistocene time. It is composed primarily of silt with secondary amounts of fine sand and clay. Like dune deposits, the loess is characteristically homogeneous throughout its extent.

UNCONSOLIDATED DEPOSITS OF TERTIARY AGE

Directly underlying the Quaternary deposits are unconsolidated deposits of Tertiary age. The deposits of Tertiary age are of continental origin. The stratigraphic units are separated by major unconformities (Figures 5-2 and 5-3). The following discussion outlines the occurrence and geology of each of the Tertiary stratigraphic units.

Ogallala Formation

As stated in the Introduction, the Ogallala Formation of Pliocene age is present throughout Region 5, and the areal extent of this Formation roughly defines the boundary of Region 5. The Ogallala Formation is separated from the overlying Quaternary sediments and the underlying Tertiary and Cretaceous sediments by unconformities (Figures 5-2 and 5-3). The Ogallala Formation is similar in lithology to the overlying Quaternary deposits, and sometimes the two cannot be differentiated (Fader et al. 1964; Hosek 1975). Commonly, the only way the units can be separated is by use of fossils.

The sediments composing the Ogallala Formation were derived primarily from the mountains to the west and were deposited by fluvial processes. The Ogallala Formation is composed primarily of interbedded unconsolidated layers of gravel, sand, silt and clay, with some consolidated layers that have been cemented by calcium carbonate (Hosek 1975). There are minor amounts of marl and volcanic ash found in the Ogallala Formation. Owing to the fluvial origin of the sediments, the Ogallala Formation characteristically grades both laterally and vertically from one type of lithology to another. Rapid facies changes occur over

short distances such that it is almost impossible to correlate a given layer from one test hole to another (Hosek 1975).

The sediments of the Ogallala Formation were deposited on a highly irregular erosional surface that had been dissected by deep narrow channels (Souders 1976; McGovern 1964); therefore the thickness of the Ogallala Formation varies greatly from place to place. In general, the sand and gravel lenses are found in the basal part of the Ogallala Formation, and carbonate material is commonly found at the top. In the literature, the carbonate "caprock" is referred to as caliche (Fader et al. 1968) in some references and as algal limestone (McGovern 1964) in others. Owing to the deposition of the Ogallala Formation on an erosional surface which represents a long period of subaerial erosion (Smith and Souders 1975), the Ogallala Formation directly overlies sediments of different ages from place to place. The Ogallala Formation may be found directly overlying older sediments of either Tertiary or Cretaceous age.

White River Group

The White River Group of Oligocene age is primarily found in the northern half of Region 5 and may be divided into two major formations: 1) the Brule Formation; and 2) the Chadron Formation. These formations are primarily found in Nebraska, Wyoming, and Colorado.

Brule Formation - The Brule Formation of the White River Group is composed primarily of calcareous siltstone with some volcanic ash layers. Occasionally sands may be found in the formation. These sands are presumably stream channel deposits. The data concerning the location

of the sands are too sparse for the sands to be mapped (Smith and Souders 1975).

Chadron Formation - The Chadron Formation of the White River Group is composed primarily of lake deposits, with some volcanic ash and some stream deposits (McGovern 1964). The bulk of the formation is clay, claystone, and silty clay, with minor amounts of sand and gravel. In general, the sand and gravel may be found near the base of the formation near the contact with the Pierre Shale (Hofstra, Major and Lucky 1972).

CRETACEOUS SEDIMENTARY ROCKS

The stratigraphy of the sedimentary rocks which are of Cretaceous age varies greatly from the northern portion of the High Plains to the southern portion of the High Plains (Figures 5-2 and 5-3). Because the surface of the Cretaceous system was subject to subaerial erosion for a long time, differential weathering removed varying amounts of the Cretaceous system at different localities (Hosek 1975). Therefore, the age of the sedimentary rocks on which the overlying Tertiary sediments were deposited varies from place to place.

Unlike the Tertiary sediments, the sedimentary rocks of the Cretaceous System are primarily marine in origin. The marine sediments were deposited by shallow seas which transgressed and regressed over the continent during Cretaceous time. Owing to the marine origins of the sedimentary rocks of Cretaceous age, the individual sedimentary layers are usually widespread, often traceable for miles. This characteristic of the Cretaceous sedimentary rocks is unlike the fluvial

sediments of the Tertiary System. The following discussion outlines the occurrence and geology of each of the Cretaceous units, beginning with the stratigraphy of the Cretaceous sedimentary rocks in the northern portion of Region 5 followed by the stratigraphy of the Cretaceous sedimentary rocks in the southern portion of Region 5 (Figures 5-2 and 5-3).

Pierre Shale

The youngest stratigraphic unit of the Cretaceous System is the Pierre Shale (Figure 5-2). The Pierre Shale is found in portions of South Dakota, Nebraska, and Colorado. In localities where it is present, it may be extremely thick, with thicknesses ranging from 2000 to 4500 feet (McGovern 1964). Owing to the marine origin of the Pierre Shale, the layers are traceable for miles, generally consisting of black, gray, and brownish shale, with some thin layers of bentonite and some calcareous concretions (Hosek 1975).

Niobrara Formation

In the northern portion of Region 5, primarily in South Dakota, Nebraska, and Colorado, the geologic unit underlying the Pierre Shale is the Niobrara Formation (Figure 5-2). The Niobrara Formation is primarily a marine chalky shale, shaley limestone, limestone, and chalk (Brogden, Shaffer and Engberg 1976; Souders 1976). In Colorado the Niobrara Formation has been separated into two members: 1) Smokey Hill Marl Member, and 2) Fort Hays Limestone Member (Hofstra, Major and Lucky 1972).

Carlile Shale

Directly underlying the Niobrara Formation in the northern portion of Region 5 is the Carlile Shale (Figure 5-2). The Carlile Shale has been separated into two stratigraphic units in Colorado: 1) Codell Sandstone Member and 2) Blue Hill Shale Member (Hofstra, Major and Lucky 1972). The Codell Sandstone Member is primarily a calcareous sandy shale with beds of very fine-grained calcareous sandstone. The Blue Hill Shale Member is a black noncalcareous shale.

Greenhorn Limestone

Directly underlying the Carlile Shale in the northern portion of Region 5 is the Greenhorn Limestone (Figure 5-2), composed primarily of gray to black interbedded limestone and shale (Hofstra, Major and Lucky 1972).

Graneros Shale

Directly underlying the Greenhorn Limestone in the northern portion of Region 5 is the Graneros Shale (Figure 5-2). This shale is primarily a fossiliferous shale with some stringers of gypsum and bentonite and thin limestone beds (Hofstra, Major and Lucky 1972).

Dakota Sandstone

Throughout the northern portion of Region 5 the Dakota Sandstone of Cretaceous age may be found. The Dakota Sandstone is of marine origin (Brogden, Shaffer and Engberg 1976) and is composed of gray to brown sandstone interbedded with sandy shale, siltstone, and clay

(Hofstra, Major and Lucky 1972). The Dakota Sandstone extends into the southern portion of Region 5 and is a major stratigraphic unit in Kansas, Oklahoma, Texas and New Mexico (Figure 5-3).

Kiowa Shale

In the southern portion of Region 5 the Kiowa Shale directly underlies the Dakota Sandstone (Figure 5-3). The Kiowa Shale is composed of gray to black silty shale with some thin sandstone beds (Fader et al. 1968).

Cheyenne Sandstone

The Cheyenne Sandstone is a major stratigraphic unit in the southern portion of Region 5 (Figure 5-2). The Cheyenne Sandstone is a fine to coarse quartzose sandstone (Fader et al. 1968).

TRIASSIC SEDIMENTARY ROCKS

In the southern portion of Region 5 sedimentary rocks of Triassic age are exposed at the surface in the Canadian River Canyon of Texas (Alexander 1961) and are also found in water wells in Texas, New Mexico and Kansas (Fader et al. 1968). The depositional environment of the Triassic sediments was continental and the Triassic sedimentary rocks are characterized by predominantly fine-grained, red sandstone and shales with minor amounts of limestone.

Dockum Group

The major stratigraphic unit of Triassic age found in the southern portion of Region 5 is the Dockum Group (Alexander 1961; Fader et al.

1968). The Dockum Group is composed of red sandstone and siltstone. The grain size of the particles in the sandstone ranges from fine sand to gravel (Fader et al. 1968).

PERMIAN SEDIMENTARY ROCKS

Sedimentary rocks of Permian age are found in the southern portion of Region 5. Very little geologic information and virtually no hydrologic information was available in the literature. In Oklahoma and Texas the Glorieta Sandstone of Permian age is used for the disposal of brines from oil fields (Irwin and Morton 1969; Alexander 1961). With so little information available on the rocks which are Permian age and older, it is not possible to evaluate these rocks for their ATEs potential and therefore, they will not be discussed further in this chapter.

HYDROGEOLOGIC FRAMEWORK

The hydrogeologic framework of the High Plains closely reflects the geologic framework established in the previous section of this chapter. The following discussion outlines the hydrogeology of Region 5 in the same format in which the geologic framework was presented.

UNCONSOLIDATED DEPOSITS OF RECENT AND PLEISTOCENE AGE

There are three principal types of unconsolidated deposits of Recent and Pleistocene age: alluvium, dunes, and loess.

Alluvium

Throughout Region 5 are aquifers associated with alluvial sands and gravels of Recent and Pleistocene age. The alluvial aquifers of Recent age are associated with present-day stream and river valleys. The alluvial aquifers of Recent age are hydrologically complex. The sands and gravels are usually not widespread and commonly interfinger with silts and clays. Aquifers range from confined to unconfined over short distances, and the thickness of the aquifers is not uniform. The yields from the alluvial aquifers of Recent age vary markedly from place to place. Reported yields range from less than 5 gallons per minute up to 3000 gallons per minute (Souders 1976; McGovern 1964; Hofstra, Major and Lucky 1972; Fader et al. 1968). The alluvial aquifers of Pleistocene age are commonly found in river terraces along present-day rivers and streams. Even though the sands and gravels associated with these aquifers are usually more extensive than the sands and gravels

associated with alluvial aquifers of Recent age, in general the terrace deposits are above the zone of saturation. However, in a few localities where wells are finished below the zone of saturation there are reported yields up to 80 gallons per minute (Souders 1976).

Dunes and Loess

The hydrologic characteristics of the dunes and loess found in Region 5 are essentially the same. Generally these deposits lie above the zone of saturation, and yields to wells are usually less than 20 gallons per minute (Hofstra, Major and Lucky 1972). However, the dunes and loess deposits are important as areas of recharge, because they absorb precipitation and transmit the water down to underlying aquifers (Hofstra, Major and Lucky 1972; Alexander 1961; McGovern 1964).

UNCONSOLIDATED DEPOSITS OF TERTIARY AGE

Ogallala Formation

The Ogallala Formation of Pliocene age is the major aquifer throughout the extent of Region 5. The geologic characteristics of the Ogallala Formation are very similar to the geologic characteristics of the alluvium of Recent and Pleistocene age. Therefore, the hydrologic characteristics of the Ogallala Formation are very similar to the hydrologic characteristics of the alluvium of Recent and Pleistocene age. Owing to the rapid facies changes of the Ogallala Formation, the hydrologic characteristics of the aquifers vary markedly from place to place. Aquifers range from confined to unconfined over short distances, and the thickness of the aquifers is not uniform.

As stated in the geologic framework section of this region chapter, the Ogallala Formation is often difficult to distinguish from the unconsolidated deposits of Recent and Pleistocene age (Fader et al. 1968). In fact, throughout Region 5 the Ogallala Formation and the overlying alluvium often act as a single aquifer (Spalding 1975; Newport 1959). Many of the wells obtain water from the alluvium and from the Ogallala Formation and therefore, the hydrologic characteristics of these wells apply both to the alluvium and to the Ogallala Formation. In much of the upland areas where the Ogallala Formation is found near the surface, it is commonly unsaturated (Smith and Souders 1975).

White River Group

As stated in the geologic framework section of this region chapter, the White River Group is divided into two distinct formations: 1) the Brule Formation; and 2) the Chadron Formation. The two formations are different lithologically and therefore are different hydrologically.

Brule Formation - The Brule Formation of the White River Group is primarily composed of fine-grained material with a few channel sand deposits. Ground-water supplies are developed primarily from fracture zones in the silt of the Brule Formation. The amount of water available to a well depends upon the number and size of the fractures, and the well yield at a particular location cannot be predicted prior to drilling (Lowry 1966; Hofstra, Major and Lucky 1972; Smith and Souders 1975). The Brule Formation is an important aquifer in many areas in the northern portion of Region 5, particularly where alluvium and the Ogallala Formation are thin or absent. Some wells report yields up to 250 gallons per minute where there is a highly developed fracture system in the Brule Formation (Hofstra, Major and Lucky 1972).

Chadron Formation - The Chadron Formation of the White River Group is also primarily composed of fine-grained material. However, in some areas of the Chadron Formation there is a basal sand and gravel at the contact with the Pierre Shale (Smith and Souders 1975; Hofstra, Major and Lucky 1972). In some areas in the northern portion of Region 5, wells that are finished in this basal sand and gravel unit are known to yield up to 1000 gallons per minute (Smith and Souders 1975). These wells are reported to be artesian but have large drawdowns, ranging from 200 to 500 feet. Pumping of water from the Chadron Formation is also reported to cause drawdowns in neighboring wells.

CRETACEOUS SEDIMENTARY ROCKS

Because the stratigraphic units of the Cretaceous Sedimentary rocks are usually widespread, owing to their marine origin, the hydrologic conditions of the aquifers associated with these rocks are generally more uniform over the extent of the aquifers than the more varied hydrologic conditions of the Tertiary unconsolidated sediments of continental origin.

Pierre Shale

Owing to the fine-grained material which makes up the Pierre Shale, the Pierre Shale is generally not a source of groundwater in Region 5. Most of the reports for Region 5 consider the Pierre Shale to be impervious (Hosek 1975; Souders 1976; Spalding 1975; McGovern 1964; etc.). However, the Pierre Shale is considered important as a hydrologic boundary between the aquifers of Tertiary and Cretaceous

age. Above the Pierre Shale the younger aquifers are often considered to be under "water-table" conditions (Hosek 1975) and below the Pierre Shale the older aquifers are often found to be under confined conditions (Souders 1976). Very small yields, less than 25 gallons per minute, are reported to be developed from the Pierre Shale from weathered zones (Hofstra, Major and Lucky 1972) and from fracture zones (Keene, Pearl and Pabst 1969).

Niobrara Formation

In the northern portion of Region 5 the Niobrara Formation is a major aquifer in many localities. In some areas of Kansas, well yields are reported to be as high as 1000 gallons per minute (Stulken et al. 1974; Gutentag and Stulken 1976). In other areas yields are reported to be small (Hofstra, Major and Lucky 1972), and in some areas the Niobrara Formation is not considered to be an aquifer at all (Newport, 1959). Ground-water supplies are developed from fracture zones and solution cavities within the Niobrara Formation (Brogden, Shaffer and Engberg 1976; Souders 1976). The amount of water available to a well depends upon the number and size of the fractures and solution cavities developed in the Niobrara Formation at a particular location. Well yields cannot be predicted prior to drilling.

Carlile Shale

As stated in the geologic framework section of this chapter, the Carlile Shale may be separated into two stratigraphic units: 1) the Codell Sandstone Member; and 2) the Blue Hill Shale Member. Small ground-water supplies are developed from the Codell Sandstone Member;

however, yields are generally much less than 50 gallons per minute (Souders 1976; Hofstra, Major and Lucky 1972). The Blue Hill Shale Member is fine-grained and does not yield water to wells (Hofstra, Major and Lucky 1972).

Greenhorn Limestone

The Greenhorn Limestone has a low permeability and is not known to yield water to wells in Region 5. It acts as a confining layer for aquifers below this unit (Hofstra, Major and Lucky 1972; Newport 1959; Simpson 1960; Souders 1976).

Graneros Shale

The Graneros Shale is hydrologically similar to the Greenhorn Limestone. The Graneros Shale has a low permeability, is not known to yield water to wells, and acts as a confining layer for aquifers below this unit (Hofstra, Major and Lucky 1972; Newport 1959; Simpson 1960; Souders 1976).

Dakota Sandstone

The Dakota Sandstone is a major aquifer found throughout Region 5. Groundwater is developed from the sandstone layers in the formation. No specific data for the hydrologic characteristics of the Dakota Sandstone Aquifer were found. In general, the information available in the literature indicates that water from the Dakota Sandstone Aquifer is too highly mineralized for most uses in the northern portion of Region 5 (Brogden, Shaffer and Engberg 1976; Sounders 1976; Newport 1959). In some areas of the northern portion of Region 5, the water is of such

poor quality that it is unsuitable for irrigation, stock, or domestic usage (Newport 1959). However, in localities where the water can be utilized for stock and domestic usage, reported well yields range from 4 to 150 gallons per minute (Sounders 1976). The wells are typically artesian, indicating confined conditions. Because of the poor water quality, the question can be raised whether the typically low yields are a reflection of the use (i.e. small pumps are usually installed in stock and domestic wells) rather than the actual capacity of the Dakota Sandstone Aquifer.

In some areas in the southern portion of Region 5, the Dakota Sandstone is the principal aquifer providing municipal and irrigation supplies (Bayne and Ward 1974; Alexander 1961). Yields up to 300 gallons per minute are reported in the literature (Stulken et al. 1974). However, throughout much of the southern portion of Region 5, the Dakota Sandstone Aquifer yields small supplies for stock and domestic wells (Fader et al. 1968). The Dakota Sandstone Aquifer also contributes water to multiple-aquifer irrigation wells. In western Kansas, this aquifer is thought to have potential for greater development as a ground-water resource, and its potential has not been fully developed because large ground-water supplies have been developed from the shallower aquifers such as the Ogallala Formation (Gutentag and Stulken 1976).

Kiowa Shale

The Kiowa Shale is a major confining layer for aquifers underlying this shale unit (Bayne and Ward 1974). The Kiowa Shale has a low permeability and yields little or no water to wells (Fader et al. 1964).

Cheyenne Sandstone

The Cheyenne Sandstone is a major aquifer in the southern portion of Region 5. Yields are reported up to 500 gallons per minute (Fader et al. 1968). Ground-water supplies for irrigation are commonly developed by use of multiple-aquifer wells such that hydrologic data for only the Cheyenne Sandstone aquifer were not available in the literature. In general, the literature indicates that the wells derive water from the Cheyenne Sandstone aquifer under confined conditions (Alexander 1961). In western Kansas the Cheyenne Sandstone aquifer is thought to have potential for greater development and this potential has not been fully developed because large ground-water supplies are developed from the shallower aquifers such as Ogallala Formation (Gutentag and Stulken 1976).

TRIASSIC SEDIMENTARY ROCKS

Dockum Group

Ground-water supplies are developed from the continental sandstones found in the Dockum Group of Triassic age. In Texas, the aquifer(s) associated with the Dockum Group contribute only small quantities of water to wells (Alexander 1961). In Kansas yields up to 1,000 gallons per minute are reported when the Dockum Group aquifer is developed for multiple-aquifer irrigation wells (Fader et al. 1968).

MAJOR AQUIFERS

For the purpose of this study, a major aquifer is identified as an aquifer with significant areal extent that can sustain yields of at least 50 gallons per minute throughout its extent. The major aquifers are determined to be either suitable or unsuitable for thermal energy storage and a discussion of each aquifer's evaluation is presented in the following sections. The previous sections of this chapter describe the geologic and hydrogeologic framework and introduce the common aquifers of Region 5.

The Hydrogeologic Framework section described the general occurrence of groundwater and discussed many water-yielding rock formations regardless of their areal extent or yield characteristics. Table 5-1 provides a listing of the major aquifers in the region. The following sections of this chapter will discuss only those aquifers described in previous sections as major aquifers.

Specific data pertaining to each major aquifer's quantitative properties are tabulated and listed according to porosity group in Table 5-2. The qualitative geologic characteristics of each hydrogeologic environment are generalized and presented in Table 5-2. The specific reference for which quantitative data is cited can be identified by checking the title of the numbered reference cited after each set of data.

Only a portion of the hydrologic data provided in the literature for wells in Region 5 is not recorded in Table 5-2. Some of the existing data were not utilized in this study because those data were reported for specific wells that often tapped more than one aquifer.

Generally it was impossible to determine which aquifers supplied water to the individual wells. Also, in some reports, such as Voegeli and Hershey (1965), the hydrologic data for a given aquifer were data from only one pump test of one well. One pump test is not conclusive and cannot define the hydrologic characteristics of an aquifer, therefore, these data are not presented in Table 5-2.

Many of the reports provided only water quality data. As determined in the Introduction, water quality by itself is not a limiting factor for development of an ATEs facility. Therefore, when only water quality data were given without any hydrologic data, the water quality data were not recorded in Table 5-2.

AQUIFERS UNSUITABLE FOR ATES

All of the major aquifers of Region 5 have been evaluated according to the guidelines established in the Introduction. On the basis of this evaluation many of the aquifers have been judged as generally unsuitable for ATES. In most cases, site-specific studies are needed to more fully evaluate the ATES potential of each aquifer. The aquifers judged at this time to be unsuitable for ATES are discussed below, together with the justification for their elimination from further consideration. Figure 5-4 provides a listing of the major aquifers in Region 5 considered unsuitable for ATES.

ALLUVIUM

As established in the Hydrogeologic Framework section, the sand and gravel aquifers associated with alluvial deposits of Recent age are capable of sustaining large yields; in many areas the well yields are greater than 1,000 gallons per minute. However, the sedimentary depositional environment associated with rivers and streams provides for rapid facies changes. As a result of these changes, the sand and gravel aquifers are generally not widespread and hydrogeologic conditions may change markedly over the extent of the aquifer. An alluvial aquifer may be confined in some areas and unconfined in other areas.

Site-specific studies may establish that alluvial sands and gravels at a particular location may be suitable for ATES. However, the regional scope of this study dictates that in general, these sub-regional aquifers should be eliminated from further consideration.

AQUIFER	REASONS FOR UNSUIT- ABLE RECOMMENDATION	COMMENTS
Alluvium	Rapid facies changes make the hydrologic conditions vary place to place; therefore aquifers are sub-regional in extent.	Site-specific studies may provide information that proves an alluvial aquifer is suitable for A.T.E.S. at a particular location.
Ogallala Formation	Rapid facies changes make the hydrologic conditions vary place to place; therefore aquifers are sub-regional in extent.	Site-specific studies may provide information that proves the aquifer is suitable for A.T.E.S. at a particular location.
Brule Formation	Fracture Porosity	All aquifers with fracture porosities are considered unsuitable for A.T.E.S. at this time owing to the random and unpredictable volumes of stored water in these aquifers.
Chadron Formation	Rapid facies changes make the hydrologic conditions vary place to place; therefore aquifers are sub-regional in extent.	Site-specific studies may provide information that proves the aquifer is suitable for A.T.E.S. at a particular location.
Niobrara Formation	Fracture Porosity	All aquifers with fracture porosities are considered unsuitable for A.T.E.S. at this time owing to the random and unpredictable volumes of stored water in these aquifers.

MAJOR AQUIFERS UNSUITABLE FOR A.T.E.S. IN REGION 5

FIGURE 5-4

OGALLALA FORMATION

The sand and gravel aquifers associated with the Ogallala Formation are capable of sustaining large yields, in many areas greater than 1,000 gallons per minute. However, the sedimentary depositional environment associated with the Ogallala Formation, that is the fluvial origin of the sediments, provides for rapid facies changes. As a result of these changes, the sand and gravel aquifers of the Ogallala Formation are similar to the alluvial aquifers. They are generally not widespread, and their hydrogeologic conditions may change markedly from one location to another. The Ogallala Formation aquifer is confined in some areas and unconfined in others.

Site-specific studies may establish that, in some locations, the Ogallala Formation aquifer is suitable for ATEs. However, the regional scope of this study dictates that, in general, these sands and gravels are sub-regional aquifers and should be eliminated from further consideration.

BRULE FORMATION

Throughout the northern portion of Region 5 the Brule Formation is a major aquifer. Ground-water supplies are obtained from fracture zones developed in the silt. As established in the aquifer evaluation guidelines of this report, aquifers associated with secondary porosities are considered undesirable for ATEs owing to their somewhat random and unpredictable volumes of stored water. Therefore, all of the fracture porosity aquifers are eliminated from further consideration for ATEs.

CHADRON FORMATION

Large ground-water supplies may be developed from a basal sand and gravel that is found at the contact between the Chadron Formation and the Pierre Shale in some localities. However, there are rapid facies changes associated with this basal sand and gravel aquifer which is a channel sand deposit. Therefore, the basal sand and gravel is not widespread and hydrogeologic conditions may change markedly over the extent of the aquifer.

Site-specific studies may establish that, in some locations, this basal sand and gravel deposit is suitable for ATEs. However, the regional scope of this study dictates that in general, this sub-regional aquifer should be eliminated from further consideration.

NIOBRARA FORMATION

Large ground-water supplies are obtained from fractures and solution cavities developed in the carbonates of the Niobrara Formation. As established in the aquifer evaluation guidelines of this report, aquifers associated with secondary porosities are considered undesirable for ATEs owing to their somewhat random and unpredictable volumes of stored water. Therefore, all of the carbonate aquifers are eliminated from further consideration for ATEs.

AQUIFERS SUITABLE FOR ATES

Data gathered on aquifers in Region 5 indicate there are several aquifers throughout the region that may be suitable for ATES. The data provided in Table 5-2 were reviewed with respect to the aquifer evaluation guidelines provided in the Introduction. Based upon the evaluation, an assessment was then made of the type of ATES storage that may be developed from an aquifer: large system chill, low or high temperature storage, or small system chill, low or high temperature storage. Figure 5-5 contains a listing of the major aquifers in Region 5 which may be suitable for ATES.

DAKOTA SANDSTONE

The Dakota Sandstone Aquifer is found throughout the extent of Region 5. In the northern portion of Region 5 the well yields are generally less than 50 gallons per minute, but this may be because of the capacity of the pumps and not a true reflection of the capacity of the aquifer. In the southern portion of Region 5 the well yields are also small and the water is used for stock and domestic wells. However, large yields are reported for wells in which the Dakota Sandstone Aquifer contributes water to multiple-aquifer wells.

Even though there is abundant general geologic information available on the Dakota Sandstone Aquifer, specific hydrologic data are difficult to find in the literature. Without sufficient hydrologic information, the aquifer's suitability for ATES was determined by what is known about the geologic conditions of the Dakota Sandstone Aquifer. As established in the geologic and hydrologic sections of this report,

AQUIFER	TYPES OF A.T.E.S. STORAGE	COMMENTS
Dakota Sandstone	Small system — high, low, chill storage	Yields in Region 5 are usually less than 50 gpm but that could be a result of the small capacity pumps which are installed in most wells. The aquifer is generally capable of greater yields.
Cheyenne Sandstone	Small system — high, low, chill storage Large system — high, low, chill storage	Not much hydrologic data for the aquifer because most wells are finished in overlying Ogallala Formation.
Dockum Group	Small system — high, low, chill storage Large system — high, low, chill storage	To little information available to adequately assess aquifers suitability for A.T.E.S.

MAJOR AQUIFERS SUITABLE FOR A.T.E.S. IN REGION 5

FIGURE 5-5

the Dakota Sandstone Aquifer is predominantly a widespread marine sand and may be confined by overlying units, such as the Pierre Shale in the northern portion of Region 5. The geologic conditions (thickness, depth, lithology) vary markedly over the region. Extensive site-specific assessment of the aquifer's suitability for ATEs should be made. Because the geologic conditions of the aquifer vary over the region, its hydrologic characteristics should also vary over the region. Without adequate information at this time, it is premature to evaluate what type of ATEs facility is feasible for the aquifer. However, because the reported yields of the Dakota Sandstone Aquifer throughout Region 5 are generally less than 500 gallons per minute, except when the aquifer is used for multiple-aquifer irrigation wells, in general the Dakota Sandstone Aquifer is probably only suitable for small system high temperature, low temperature, or chill storage.

CHEYENNE SANDSTONE

Hydrologic data for the Cheyenne Sandstone Aquifer are lacking. However, in general, it is known that the Cheyenne Sandstone Aquifer is capable of sustaining yields up to 500 gallons per minute and that the aquifer is confined. In western Kansas this aquifer is thought to have potential for greater development, and the aquifer's potential has not been fully developed because large ground-water supplies are developed from the shallower aquifers such as the Ogallala Formation. The aquifer may be capable of sustaining yields greater than 500 gallons per minute. Without sufficient hydrologic information, the aquifer's suitability for ATEs was determined by what is known about the geologic conditions of the Cheyenne Sandstone Aquifer. Without adequate

information at this time, it is premature to evaluate what type of ATEs facility is feasible for the aquifer. It may be found after further study that there are areas of the aquifer which may be suitable for each of the different types of storage (i.e. large system chill, low or high temperature storage; small system chill, low or high temperature storage).

DOCKUM GROUP

There is very little geologic information and virtually no hydrologic data available in the literature for the aquifer(s) associated with the Dockum Group. Therefore, an adequate assessment of the ATEs potential of the aquifer(s) cannot be made at this time. However, the limited information available indicates that the aquifer(s) associated with the Dockum Group may be suitable for ATEs, and there was no information presented to justify elimination of the Dockum Group aquifer(s) from further consideration. It may be found after further study that there are areas of the aquifer suitable for each of the different types of storage (i.e. large system chill, low or high temperature storage; small system chill, low or high temperature storage).

REGION'S ATES POTENTIAL

Several aquifers in Region 5 show potential for thermal energy storage. The aquifers which regionally show the most promise for ATES are the widespread sandstones of Cretaceous age: 1) the Dakota Sandstone; and 2) the Cheyenne Sandstone. The Dockum Group aquifer has insufficient information at this time to adequately assess its suitability for ATES; however, there was no information available in the literature indicating that the aquifer is unsuitable for ATES. In all cases, site-specific information is needed before development of an ATES facility is considered.

Owing to the regional scope of this study, only the regional aquifers of Region 5 were considered for ATES potential, and only the most recent and available literature was reviewed. Site-specific information may possibly prove that aquifers other than those cited above have potential for ATES at particular localities. This is particularly true for the Ogallala Formation, which extends over the entire region and yields tremendous volumes of water. The purpose of this regional study is to determine the aquifers appearing to have the greatest potential for ATES and should not preclude site-specific investigations.

REFERENCES CITED

- Alexander, W. H., Jr., 1961, Geology and ground-water resources of the Northern High Plains of Texas, progress report no. 1: Texas Board of Water Engineers bulletin 6109, 39 p.
- Bayne, C. K., and Ward, J. R., 1974, Geology and hydrology of Rice County central Kansas: Kansas Geol. Survey in coop. with the U.S. Geol. Survey, Bulletin 206, Part 3, 17 p.
- Brogden, R. E., Shaffer, F. B., and Engberg, R. A., 1976, Water resources of Pierce County Nebraska: U.S. Geol. Survey in coop. with Conservation and Survey Division, University of Nebraska, Nebraska Water Survey Paper Number 41, 35 p.
- Engberg, R. A., and Spalding, R. F., 1978, Groundwater quality atlas of Nebraska: U.S. Geol. Survey in coop. with Nebraska Water Resources Center, Resource Atlas No. 3, 39 p.
- #027 Fader, S. W., et. al., 1968, Geohydrology of Grant and Stanton Counties, Kansas: U.S. Geol. Survey in coop. with State Geol. Survey of Kansas, Bulletin 168, 145 p.
- Geraghty, J. J., et. al. , 1973, Water atlas of the United States: Water Information Center, Port Washington, New York, 122 Plates.
- Gutentag, E. D., and Stulken, L. E., 1976, Ground-water resources of Land and Scott Counties Western Kansas: Kansas Geol. Survey in coop. with the U.S. Geol. Survey, Irrigation Series No. 1, 37 p.
- Hofstra, W. E., Major, T. J., and Luckey, R. R., 1972, Hydrogeologic data for the Northern High Plains of Colorado: Colorado water conservation Board Basic Data Release No. 23, 143 p.
- Hosek, R. J., 1975, Quantitative hydrogeology and evaluation of water-management alternatives, Mira Valley area in Valley County, Nebraska: unpublished Masters Thesis, University of Nebraska, 196 p.
- Irwin, J. H., and Morton, R. B., 1969, Hydrogeologic information on the Glorieta Sandstone and the Ogallala Formation in the Oklahoma panhandle and adjoining areas as related to underground waste disposal: U.S. Geol. Survey Circular 630, 26 p.
- Keene, K. M., Pearl, R. H., and Pabst, M. E., 1969, Hydrogeologic data from Cheyenne, Decatur, Rawlins, Sheridan, Sherman and Thomas Counties, Kansas: U.S. Geol. Survey in coop. with State Geol. Survey of Kansas, Kansas Ground Water Basic Data Release No. 1, 113 p.

REFERENCES CITED (CONTINUED)

- Lowry, M. E., 1966, The White River Formation as an aquifer in southeastern Wyoming and adjacent parts of Nebraska and Colorado: U.S. Geol. Survey Prof. Paper 550-D, pp. D217-D222.
- McGovern, H. E., 1964, Geology and ground-water resources of Washington County Colorado: U.S. Geol. Survey Water Supply Paper 1777, 46 p.
- Newport, T. G., 1959, Ground-water resources of the lower Niobrara River and Ponca Creek basins, Nebraska and South Dakota: U.S. Geol. Survey Water Supply Paper 1460-G, 323 p.
- Simpson, H. E., 1960, Geology of the Yankton area South Dakota and Nebraska: U.S. Geol. Survey Prof. Paper 328, 123 p.
- Souders, U. L., 1976, Physiography, geology, and water resources of Boyd County, Nebraska: U.S. Geol. Survey in coop. with Conservation and Survey Division, University of Nebraska, Nebraska Water Survey Paper Number 42, 113 p.
- Smith, F. A., and Souders, U. L., 1975, Groundwater geology of Banner County, Nebraska: Conservation and Survey Division, University of Nebraska, Nebraska Water Survey Paper Number 39, 96 p.
- Spalding, 1975, Land use and river seepage on groundwater quality in Hall County, Nebraska: Conservation and Survey Division, University of Nebraska, Nebraska Water Survey Paper Number 38, 95 p.
- Stulken, L. E., et. al., 1974, Hydrogeologic data from Greeley, Wichita, Scott, and Lane Counties, Kansas: Kansas Geol. Survey in coop. with the U.S. Geol. Survey Basic Data Series Ground-water Release No. 4, 58 p.
- Voegeli, P. T., and Hershey, L. A., 1965, Geology and ground-water resources of Prowers County, Colorado: U.S. Geol. Survey Water-Supply Paper 1772, 101 p.

GENERAL REFERENCES

The following references for Region 5 were reviewed but are not cited in the report.

- Boettcher, A. J., 1964, Geology and groundwater resources in Eastern Cheyenne and Kiowa Counties, Colorado: U.S. Geol. Survey Water-Supply Paper 1779-N, 32 p.
- #028 Boettcher, A. J., 1966, Ground-water development in the High Plains of Colorado: U.S. Geol. Survey Water-Supply Paper 1819-I, 22 p.
- Bradley, Edward, 1956, Geology and ground-water resources of the upper Niobrara River Basin, Nebraska and Wyoming: U.S. Geol. Survey Water-Supply Paper 1368, 70 p.
- #029 Cardwell, W. D. E., and Jenkins, E. D., 1963, Ground-water geology and pump irrigation in Frenchman Creek basin above Palisade, Nebraska: U.S. Geol. Survey Water-Supply Paper 1577, 472 p.
- Exner, M. E., and Spalding, R. F., 1974, Groundwater quality of the central Platte region: Conservation and Survey Division, University of Nebraska, 48 p.
- Gutentag, E. D., et. al., 1972, Groundwater in Finney County, southwestern Kansas: U.S. Geol. Survey Hydrol. Inv. tlas HA-442.
- Gutentag, E. D., and Stulken, L. E., 1974, Groundwater in Haskell County, southwestern Kansas: U.S. Geol. Survey Hydrol. Inv. Atlas HA-515.
- Hodson, W. G., 1969, Geology and ground-water resources of Decatur County, Kansas: U.S. Geol. Survey in coop. with State Geol. Survey of Kansas, Bulletin 196, 41 p.
- Johnson, C. R., 1960, Geology and ground-water in the Platte-Republican Rivers watershed and the Little Blue River basin above Angus, Nebraska: U.S. Geol. Survey Water-Supply Paper 1489, 142 p.
- Keech, C. F., 1962, Ground-water resources of Hamilton County Nebraska: U.S. Geol. Survey Water-Supply Paper 1539-N, 64 p.
- Keech, C. F., Dreeszen, U. H., and Emery, P. A., 1967, Availability of ground water in York County, Nebraska: U.S. Geol. Survey Water-Supply Paper 1839-F, 17 p.
- Layton, D. W., and Berry, D. W., 1973, Geology and ground-water resources Pratt County south-central Kansas: State Geol. Survey of Kansas in coop. with the U.S. Geol. Survey, Bulletin 205, 33 p.
- #030 Lowry, M. E., and Crist, M. A., 1967, Geology and ground-water resources of Laramie County Wyoming: U.S. Geol. Survey Water-Supply Paper 1834, 71 p.

GENERAL REFERENCES (CONTINUED)

- McClain, T. J., et. al., 1975, Water resources of Cove, Logan, and Wallace Counties, west-central Kansas: U.S. Geol. Survey Hydrol. Inv. Atlas HA-521.
- McGovern, H. E., 1974, Geology and ground water in the Ogallala Formation and undifferentiated Pleistocene deposits, southwestern Kansas: Kansas Geol. Survey, 29 p.
- Morton, R. B., 1973, Preliminary investigations of the hydrogeology of the Permian to Tertiary rocks of the Oklahoma Panhandle: U.S. Geol. Survey Map I-738.
- Morton, R. B., and Goemaat, R. L., 1973, Reconnaissance of the water resources of Beaver County, Oklahoma: U.S. Geol. Survey Hydrol. Inv. Atlas HA-450.
- Pettyjohn, W. A., et. al., 1972, A ground-water quality atlas of the United States: Research Section of the National Water Well Association for National Demonstration Water Project, 272 p.
- Rapp, J. R., Visher, F. N., and Littleton, R. T., 1957, Geology and ground-water resources of Goshen County, Wyoming: U.S. Geol. Survey Water-Supply Paper 1377, 145 p.
- Sapik, D. B., and Goemaat, R. L., 1973, Reconnaissance of the ground-water resources of Cimarron County, Oklahoma: U.S. Geol. Survey Hydrol. Inv. Atlas HA-373.
- Stulken, L. E., and Fader, S. W., 1976, Hydrogeologic data from the Great Bend Prairie, south-central Kansas: Kansas Geol. Survey in coop. with U.S. Geol. Survey, Basic Data Series Ground-Water Release No. 5, 50 p.
- University of Nebraska, 1969, Groundwater atlas of Nebraska: U.S. Geol. Survey in coop. with Conservation and Survey Division, University of Nebraska, 7 Plates.
- Weeks, E. P., 1974, Hydrologic conditions in the Wheatland Flats area, Platt County Wyoming: U.S. Geol. Survey Water-Supply Paper 1783, 78 p.
- Weist, W. G., Jr., 1964, Geology and ground-water resources of Yuma County, Colorado: U.S. Geol. Survey Water-Supply Paper 1539-J, 56 p.
- Wood, P. R., and Hart, D. L., Jr., 1967, Availability of groundwater Atlas HA-250.

Region 6. Glaciated Central Lowland

REGION 6 - GLACIATED CENTRAL REGION

INTRODUCTION

Region 6 encompasses the area of the mid-continent which has been periodically covered by continental ice masses during the Pleistocene Epoch. The area extends from the plains of Montana east of the Rocky Mountains to the plateau regions of New York and Pennsylvania west of the Appalachians. The boundary of the region is defined by the Missouri River in the west and by the southern terminus of maximum glaciation in the east. The boundary is not coincident with the Ohio River for most of the eastern portion of the region. However, the Ohio River does lie within the region in the southeastern portion of Indiana and the southwestern portion of Ohio (Figure 6-1).

The average annual precipitation varies markedly over the region. In general, the trend is from the semi-arid plains states in the western part of the region, which receive 10 to 20 inches of precipitation per year, through the mid-continent area, which receives 30 to 40 inches of precipitation per year, to the eastern portion of the region, which receives as much as 40 to 60 inches of precipitation per year (Geraghty et al. 1973). In the semi-arid portion of Region 6, there is a salinity problem which has developed in the surficial aquifers as a result of the dry climate (Reeder 1978).

Ground-water usage also varies markedly across the region. In the east and mid-continent areas, ground-water resources are used primarily for drinking water and are the major supply for many of the

REGION 6 GENERAL OUTLINE

FIGURE 6-1

large metropolitan areas. In the western plains areas groundwater is used for irrigation as well as drinking water.

GEOLOGIC FRAMEWORK

RECENT AND PLEISTOCENE UNCONSOLIDATED DEPOSITS

The dominant surficial geology and present physiography of Region 6 may be attributed to the continental ice masses which covered the region during the Pleistocene Epoch. The retreat of the glaciers left the area blanketed with a veneer of unconsolidated material, in some areas as much as 400 to 500 feet thick. The two major types of unconsolidated material deposited during the Pleistocene Epoch were a pebbly clay material called till, and sand and gravel deposits called outwash. Both types of material blanket the entire region.

As a result of the glaciers' advance and retreat many of the major drainages were altered dramatically. Some of the major streams had their courses relocated (i.e. the Mississippi River and Missouri River). The abandoned channels of the old river valleys were filled with glacial material such that there is no surficial expression of their existence today. These valleys are called "buried valleys". The most renowned of the buried valleys is perhaps the Mahomet or Teays buried valley, which was the location of a major pre-Pleistocene river which flowed from West Virginia through central Ohio, Indiana, and Illinois. Seismic information indicates that the ancient bedrock valley was in excess of 400 feet deep and yet, there is no evidence on the surface that the valley exists. The valley is filled with thick alternating sequences of outwash layers and till layers.

After the glaciers retreated, present-day rivers and streams filled their valleys with alluvium. The alluvium of Recent age consists of silt and clay flood plain deposits and sands and gravels associated with channels and point bars. The present-day streams which did not have their courses relocated during the Pleistocene Epoch have valleys filled with both Recent-aged alluvium and Pleistocene outwash.

BEDROCK

The bedrock of Region 6 can be separated into two major provinces and shows a trend from east to west. The bedrock underlying the surficial unconsolidated deposits of the eastern and mid-continent portions of Region 6 is a thick sequence of Paleozoic sedimentary rocks. The bedrock underlying the surficial unconsolidated deposits in the western portion of Region 6 is either late Mesozoic or Cenozoic sedimentary rocks. There is a transition zone between the two provinces in western Minnesota and Iowa where there is a relatively thin sequence of Mesozoic and Cenozoic rocks overlying the Paleozoic rocks. In northern Minnesota, Wisconsin, and the Upper Peninsula of Michigan, the surficial unconsolidated deposits are underlain by Precambrian crystalline basement and meta-sedimentary rocks of the Canadian shield (Figure 6-2).

Eastern and Mid-Continent Paleozoic Rocks

The Paleozoic sedimentary rocks of the eastern and mid-continent portions of Region 6 are predominantly sandstones, shales, and carbonates of marine origin. These marine rocks were deposited when the North American Continent was periodically covered by shallow epeiric seas during early and middle Paleozoic time. During late Paleozoic time (Pennsylvanian and Permian Periods) the North American Continent

GENERAL DISTRIBUTION OF PALEOZOIC, MESOZOIC
AND CENOZOIC, AND PRECAMBRIAN ROCKS

FIGURE 6-2

emerged and the sedimentary rocks fluctuate between those that are of marine origin and those that are of continental origin.

The Permian and Pennsylvanian rocks have lithologies that reflect either continental, deltaic or near-shore depositional environments. There are rapid facies changes in the Pennsylvanian rocks from shale, limestone, sandstone, and coal. The sequential pattern of these lithologies is called a "cyclothem". It is important to note that the sandstones of Pennsylvanian age not widespread blanket sands of marine origin, but rather the sandstones are channel sands of continental origin.

Throughout the eastern and mid-continent areas of Region 6 the Paleozoic rocks of Mississippian, Devonian, and Silurian ages are predominately massive units of carbonates (limestones and dolomites). Where the carbonate units are found they may be several hundred feet to a thousand feet thick. These thick carbonate units are evidence that the North American Continent was covered by epeiric seas for several hundred million years.

Late Ordovician time is represented in Region 6 by a thick sequence of shale as much as 400 to 500 feet in thickness. Middle Ordovician rocks are massive carbonates. Early Ordovician and Cambrian rocks are dominated by a series of widespread blanket sandstones. These sandstones were deposited as the seas transgressed and regressed over the continent. The composition of the sandstones ranges within each unit from quartzose to dolomitic.

The Paleozoic sedimentary rocks of the east and mid-continent were deposited upon ancient Precambrian crystalline basement rocks. The

basement provides the structural framework and indicates that continental tectonics have been active since Precambrian time. Throughout the continental platform there is a series of structural basins and arches (Bloyd 1974). The major structural basins located in Region 6 are: Illinois Basin, Iowa Basin, Michigan Basin, and Williston Basin. The major arches or structurally high areas are: Cincinnati Arch, Findley Arch, Kankakee Arch, and the Sioux Arch (Figure 6-3). All of the Paleozoic rocks thin out to the north and the Precambrian meta-sedimentary rocks and crystalline basement rocks are exposed. Throughout the region, the Paleozoic rocks provide evidence of differential erosion since Precambrian time. The area where the ancient crystalline rocks are exposed is called the Canadian Shield.

Western Plains Late Mesozoic and Cenozoic Rocks

The bedrock directly underlying the surficial unconsolidated deposits in the western plains area of Region 6 is predominantly sandstones, shales, and coals of marine and continental origin. These rocks consist of material derived from the uplift of the Rocky Mountains and deposited at the continental margin during Early Cenozoic time. The rock sequence reflects a transition from marine sediment deposition during Early Cretaceous time to deposition of continental sediments from Late Cretaceous through Tertiary time.

The widespread marine sedimentary units deposited during Cretaceous time are commonly referred to as the Dakota Sandstone, the Pierre Shale, and Fox Hills Sandstone (Reeder 1978). The Hell Creek Formation, which directly overlies the Fox Hills Sandstone, is composed of alternating layers of shale, sandstone, sand, gravel, and clay, with some lignite lenses. The Hell Creek Formation of Late Cretaceous age

REGION 6 GENERALIZED STRUCTURAL FRAMEWORK

represents the transition from marine to continental deposition. The Tertiary rocks, primarily the Fort Union Formation, represent continued continental deposition of sediments throughout the western portion of Region 6.

The Cretaceous and Tertiary units of Minnesota and North Dakota dip toward the west, toward the Williston Basin (Reeder 1978). The center of the Williston Basin lies in northwestern North Dakota, and the basin extends into northeastern Montana. Within the Williston Basin area, the Cretaceous and Tertiary sedimentary rocks are underlain by a thick sequence (many thousands of feet) of sedimentary rocks of lower Mesozoic and Paleozoic ages. The Madison Group of Mississippian age is a thick sequence of limestones and dolomites occurring throughout the far western portion of Region 6. The Williston Basin area is known for its oil and gas production from the Paleozoic rocks, and coal reserves in the Tertiary rocks.

HYDROGEOLOGIC FRAMEWORK

As discussed in the Geologic Framework section of this region, the occurrence of groundwater may also be separated into three primary hydrogeologic complexes: 1) the Recent alluvium and Pleistocene unconsolidated surficial deposits; 2) the Paleozoic sedimentary rocks of the east and mid-continent; and 3) the Late Mesozoic and Tertiary sedimentary rocks of the western plains.

RECENT ALLUVIUM AND PLEISTOCENE UNCONSOLIDATED DEPOSITS

Throughout the entire extent of Region 6, there are major widespread aquifers associated with the sands and gravels of Recent alluvial and glacial origin. Many of the aquifers are associated with present-day

river valleys, such as the Missouri, the Mississippi, the Ohio, and sub-ordinant streams. There are also major widespread sand and gravel aquifers associated with the buried valleys which are no longer visible at the surface, such as the Mahomet Valley, and the abandoned course of the Mississippi River (Figure 6-4). The silts and clays of Recent and Pleistocene time yield little water to wells.

The alluvial aquifers of Recent age are hydrologically complex. The sands and gravels are usually not widespread and commonly inter-finger with silts and clays. Aquifers range from confined to unconfined over short distances, and the thickness of the aquifers is not uniform. However, alluvial aquifers are capable of high sustained yields owing to rapid recharge, often from their hydraulic connection with surface water.

The aquifers associated with Pleistocene outwash are usually easier to model than the Recent alluvial aquifers. Outwash deposits are usually widespread, of uniform thickness and depth, and commonly confined by overlying till or glacial lacustrine deposits. These aquifers can usually be found at the base of the river valleys overlying the bedrock. Even though the outwash aquifers are commonly confined, they usually are capable of high sustained yields owing to their widespread characteristics.

EASTERN AND MID-CONTINENT PALEOZOIC ROCKS

As established in the Geologic Framework section of this report, the Paleozoic sedimentary rocks of the east and mid-continent in general range from the continental deposits of Permian and Pennsylvanian ages, to predominantly carbonates of Mississippian, Devonian, and Silurian ages, to massive shales of Late Ordovician age, to a thick sequence of

LOCATION OF THE BURIED MAHOMET RIVER VALLEY AND
BURIED ABANDONED CHANNEL OF THE MISSISSIPPI RIVER

carbonates of Middle Ordovician age, to predominantly blanket transgressive sandstones of the Early Ordovician and Cambrian ages. The hydrogeologic framework differs according to the different sedimentary environments and rock types. This framework is an obvious simplification of the Paleozoic record and does not take into account the massive evaporite deposition in the Michigan and Williston Basins, or the intermittent shales between sandstones and carbonates. However, the above simplified geologic framework is adequate for understanding the regional hydrogeologic framework. The following discussion describes the hydrogeologic framework for all of the Paleozoic systems.

Permian and Pennsylvanian Systems

Throughout Permian time the North American continental platform was exposed above sea level. During this time erosion was the dominant force and virtually no Permian-aged rocks may be found within Region 6. However, rocks representing Pennsylvanian time indicate that deposition of sediments during the Pennsylvanian period fluctuated between continental, deltaic, and near-shore marine environments. The rapid facies changes suggest that the continental platform was "fluttering" up and down (Dott and Batten 1971).

As stated in the Geologic Framework section, rocks of Pennsylvanian age may be shales, limestones, sandstones or coals, and the pattern of these lithologies is called a "cyclothem". Very small water supplies may be developed from the shales, limestones and coals owing to fracture systems and solution cavities that have developed in the rocks. Small to moderate supplies may be developed in the sandstones. However, the amount of water the sandstones will yield at a particular location cannot be predicted prior to drilling because the sandstones are

not widespread but are channel sandstones (Selkregg and Kempton 1958).

The quality of the water from rocks of Pennsylvanian age is usually poor. Potable water supplies may be developed from Pennsylvanian sandstones but the iron content is usually higher than desired.

Mississippian System

In many areas of Region 6 the principal aquifers are of Mississippian age. The predominant lithologies of these aquifers are limestones and dolomites. Groundwater is obtained from fracture systems and solution cavities that have developed in the rock. Yields ranging from 200 gallons per minute to 1,000 gallons per minute are common, and many cities in Illinois, Iowa, Ohio, and Michigan rely upon the Mississippian aquifers for drinking water supplies. The Keokuk-Burlington Limestone (Bergstrom 1956) in Illinois is probably the most widely developed and best understood of all the Mississippian aquifers. Whereas sustained high yields are available from the Mississippian aquifers, the success of a well in these aquifers cannot be predicted before drilling.

Devonian System

The Devonian-age sedimentary rocks vary from the eastern part of Region 6 to the mid-continent area of Region 6. In the east the lithology of the Devonian age sedimentary rocks varies from shale, sandstone and limestone units in the upper section, to predominantly limestone units in the lower section (Waller, Turk and Dingman 1978). The facies changes in the upper section of the Devonian may reflect the onlap of a marine sequence onto the Appalachian Uplift during Devonian time. The sediments were deposited in the subsiding Appalachian trough. The

limestones of the lower section of the east are like the limestones of Devonian age in the mid-continent portion of Region 6. The massive limestones of the mid-continent portion of Region 6 are capable of yielding large quantities of water. Like limestone sequences mentioned previously, groundwater is available to a well because of fractures and solution cavities developed in the rock. The yield at a given locality cannot be predicted prior to drilling.

Silurian System

The Silurian System is represented in the east and mid-continent areas of Region 6 by a thick sequence of massive limestones and dolomites that resulted from large reef complexes developing in the areas during Silurian time (Dott and Batten 1971). The reef complex is believed to have completely encircled the Michigan Basin causing evaporite deposition in the interior of the basin from the restricted water circulation. The Silurian age evaporite complex (salt and gypsum) found in Michigan is not a major ground-water resource owing to the limited water yields and known poor water quality. However, the massive limestones and dolomites of Silurian age are major aquifers in Wisconsin, Illinois, Indiana, Ohio and New York.

Silurian-aged limestones and dolomites are exposed along the structural arches of the eastern and mid-continent areas of the continental platform (Norris and Fidler 1971). In these areas the Silurian limestones and dolomites are major aquifers, and directly underlie the unconsolidated Pleistocene deposits. This also means that the Silurian aquifers are essentially unconfined. Because the Silurian limestones and dolomites are often in contact with thick outwash deposits, these aquifers are rapidly recharged and can sustain high yields. The Silurian

aquifers provide drinking water to major population centers in Wisconsin, Illinois, Indiana, Ohio and New York. The Niagaran Dolomite and Lockport Dolomite are two of the major Silurian formations which are widely developed. As with the other limestone and dolomite aquifers, water is available to a well through fracture systems and solution cavities. These fracture systems and solution cavities are especially well developed in structurally high areas (Norris and Fidler 1971).

Ordovician System

During Ordovician time the deposition of sedimentary rocks changed from predominantly widespread blanket sandstones of Early Ordovician age, to carbonates (limestones and dolomites) of Middle Ordovician age, to shales of Late Ordovician age. Because the sandstones of Early Ordovician age are hydrologically connected to the sandstones of Cambrian age, and because wells usually receive water from units of both ages, discussion of their hydrology is reserved for the next section.

The thick sandstone units of Early Ordovician age (along with the sandstones of Cambrian age) are some of the most reliable and highest-producing aquifers (yields often in excess of 1,000 gallons per minute) in the Paleozoic sequence. The carbonates of Middle Ordovician age are also major aquifers and may yield up to 200 gallons per minute depending upon the degree of fracturing in the rock. The thick shale sequence of Late Ordovician age may be regarded as an aquiclude and provides confinement for the major aquifers below this unit.

Cambrian System

The eastern and mid-continent areas of Region 6 are blanketed by a series of Early Ordovician-and Cambrian-aged transgressive and regressive sandstones. In many areas where these sandstones are found

they are utilized for municipal drinking water supplies. The metropolitan area of Chicago, for example, relies upon these sandstones as the primary source for water.

Where both the Ordovician and upper Cambrian sandstones occur, wells are open to all of the sandstone units, thereby deriving water from each unit. Because the percentage of water contributed by each sandstone cannot usually be calculated, hydraulic properties for each sandstone cannot be calculated. Therefore, all of the sandstones are grouped together and the combined series of sandstones are commonly referred to as the Cambro-Ordovician Aquifer (Hughes, Kraatz and Landon 1966).

The depth to the Cambro-Ordovician Aquifer is coincident with the structural framework of the continental platform. Upper Cambrian- and Ordovician-aged sandstones are exposed at the surface in Minnesota and Wisconsin where the sandstones onlap the Canadian Shield. The sandstone units are at shallow depths in the structurally high areas (arches) of the continental platform, and are at great depths (more than 5,000 feet) in the center of the basins. The dip of the sandstones is usually less than one foot per mile (Hughes et al. 1966).

The water of the Cambro-Ordovician Aquifer becomes increasingly saline downgradient. Therefore, the water from the Cambro-Ordovician Aquifer at locations over the structural basins usually exceeds 3,000 milligrams per liter (mg/l) total dissolved solids and is not used for drinking water supplies (Prickett et al. 1964; Waller, Turk and Dingman 1978). In the basins where the Cambro-Ordovician Aquifer is deep and the water is not potable, the aquifer is commonly used for waste injection (Waller, Turk and Dingman 1978). It is assumed that the hydraulic gradient is toward the center of the basin, and therefore there

is no risk of contaminating drinking water by the injected wastes. However, research indicates that the ground-water flow is not as simple as the model suggests. Temperature anomalies in the Illinois Basin suggest that groundwater from the deep aquifers is discharging upward through fractures developed in the overlying rocks (Cartwright 1970). Data from this research indicate that even though this phenomenon is a concern for waste isolation, it is probably not a concern for considering the aquifer for ATEs suitability.

The composition of the Cambrian- and Ordovician-aged sandstones ranges from quartzose to dolomitic. The sandstones characteristically consist of well-sorted, rounded sand particles which are not well cemented. Pump test data from wells finished in these sandstones indicate that porosities of these sandstones range from 10 to 15 percent (Horick 1970).

Where the Cambro-Ordovician Aquifer is overlain by a thick sequence (usually greater than 500 feet) of younger units, the aquifer is confined. Static water level in these wells rises several hundred feet above the top of the Cambro-Ordovician Aquifer (Prickett et al. 1964). Well yields are sustained typically in excess of 1,000 gallons per minute. In metropolitan areas where tremendous pumping cones have been developed, such as Chicago, water levels in the Cambro-Ordovician Aquifer have been declining over time (Prickett et al. 1964).

Precambrian System

In the Canadian Shield area of Region 6, Precambrian crystalline basement and meta-sedimentary rocks directly underlie the surficial unconsolidated deposits. Small to moderate ground-water supplies are developed from the Precambrian rocks from fracture systems. The

amount of water available to a well depends upon the degree of fracturing. The well yield at a given location cannot be predicted prior to drilling.

WESTERN PLAINS LATE MESOZOIC AND CENOZOIC SEDIMENTARY ROCKS

The bedrock underlying the unconsolidated deposits in the western plains area of Region 6 is predominantly a sequence of sedimentary rocks deposited during Late Mesozoic (Cretaceous) and Cenozoic (Tertiary) time. As established in the geologic framework section of this report, the rock sequence reflects a transition from marine sediment deposition during the Early Cretaceous to deposition of continental sediments from Late Cretaceous through the Tertiary. The major bedrock aquifers in the region are associated with these sedimentary rocks. The major bedrock aquifers in this area of Region 6 are coincident with the geologic formations and are referred to by their formational names: Dakota Sandstone, Pierre Shale, Fox Hills-Hell Creek Aquifer (formations are combined to form one aquifer), and Fort Union Aquifer (Reeder 1978). The following sections generally describe each of these formations and their hydrogeologic characteristics.

The Late Mesozoic and Cenozoic sedimentary rocks onlap the older Paleozoic rocks in Minnesota and Iowa. This area was referred to as the "transition zone" in the Geologic Framework section of this report (Figure 6-2). In the area of the transition zone, many wells are finished in the underlying Paleozoic rocks, such as the Cambro-Ordovician Aquifer. The properties of these Paleozoic aquifers are similar to properties of the Paleozoic aquifers in the east and mid-continent areas of Region 6 (Horick 1970); therefore, there is no need to discuss the Paleozoic aquifers again.

In the far western portion of Region 6, data are insufficient to determine the areal extent, thickness, and degree of interconnection of the individual Paleozoic units. Therefore, all the Paleozoic rocks are grouped together and referred to as the Paleozoic Aquifer (Reeder 1978).

Paleozoic Aquifer

The Paleozoic Aquifer in the far western portion of Region 6 is composed primarily of a sequence of fine-grained sandstones and cavernous limestones. Devonian time is represented in the Williston Basin by a series of evaporites. The Madison Limestone of Mississippian age is a major aquifer of the region.

The depth to the top of the Paleozoic Aquifer follows the structural contour of the area. The top of the aquifer occurs at depths of about 150 feet in eastern North Dakota and deepens westward to more than 13,000 feet at the bottom of the aquifer in western North Dakota at the center of the Williston Basin (Reeder 1978).

Yields from wells finished in the Paleozoic Aquifer vary from small yields (less than 50 gallons per minute) from the fine-grained sandstones, to large yields (in excess of 200 gallons per minute) from the cavernous limestones.

Salinity of the water is a recurring problem of the aquifer and limits its usefulness. The water is generally not used for drinking water purposes. Water from the Paleozoic Aquifer is withdrawn with oil in the western part of the region.

Dakota Sandstone Aquifer

The Dakota Sandstone Aquifer is a widespread sedimentary sequence of sandstones and shales found in Iowa, Nebraska, Minnesota, South Dakota, North Dakota, and Montana. The Dakota Sandstone is

basically a marine sandstone of Early Cretaceous age. The depth to its top is coincident with the structural framework of the continental platform (Schoon 1971). The thickness of the Dakota Sandstone Aquifer is also coincident with the structural framework and ranges from 30 feet to more than 450 feet (U.S.G.S. 1975; and Reeder 1978).

The Dakota Sandstone is not uniformly permeable, but may contain two to seven very permeable zones, particularly where the aquifer is more than 50 feet thick. Water in this aquifer is commonly under artesian pressure and flows from wells, but in some areas the water must be pumped. Yields from this aquifer vary greatly over the region depending upon the thickness of the sand lenses versus the shale lenses, and depending upon the interstitial silt or clay content. Discharges from flowing wells finished in the Dakota Sandstone Aquifer range from less than one gallon per minute to 100 gallons per minute. Pumping rates vary from less than 30 gallons per minute to 500 gallons per minute, to as large as 1,500 gallons per minute (U.S.G.S. 1975; Reeder 1978).

The water quality of the Dakota Sandstone Aquifer varies greatly over the region and governs how the water is used. Water in the Dakota Sandstone Aquifer contains from 1,700 milligrams per liter (mg/l) to more than 8,000 milligrams per liter (mg/l) total dissolved solids. Water from the aquifer also varies laterally and vertically in composition of the predominant ions (U.S.G.S. 1975). Within the Williston Basin, where the salinity is highest, the dominant ions are sodium and chloride. Eastward the dominant ions in the lower parts of the aquifer are calcium, magnesium, and sulfate. However, to the east the predominant ion in the lower part of the aquifer is sodium. There are also areas where

the dominant ions are sodium and bicarbonate; or mixtures of sodium, magnesium, and calcium; or mixtures of bicarbonate, chloride and sulfate (U.S.G.S. 1975). In the areas where the total dissolved solids are low, the water is used for domestic and municipal supplies, stock use, and irrigation supplies. In the areas where the total dissolved solids are high, such as the Williston Basin area, the water from the aquifer is used mostly by the oil industry for maintaining pressure in oil reservoirs (Reeder 1978).

Pierre Shale Aquifer

The Pierre Aquifer is in the upper part of the Pierre Shale of Cretaceous age where the shale has been fractured. The Pierre Shale is composed of shale, marlstone, and claystone; where these units are unfractured they are impermeable and will not yield significant amounts of water to a well. Where fractures are present the most successful wells are finished within 100 feet below land surface. In general, only small yields can be anticipated from wells finished in the Pierre Shale; the yields are often less than six gallons per minute. However, the Pierre Aquifer may be the only source of water for farms and a few municipal supplies. Locally, where the fracture zone is exceptionally thick or the fractures unusually large, pumping rates range from 50 gallons per minute to 100 gallons per minute. These unusual conditions cannot be predicted prior to drilling.

Fox Hills-Hell Creek Aquifer

The Fox Hills Formation and Hell Creek Formation are hydrologically connected and are considered as a single aquifer. The aquifer is composed of interbedded sand, clay, silt, and lignite and the lithology varies greatly from place to place (Reeder 1978). The lower part of

the aquifer, Fox Hills Formation, consists of sandstone and sandy shale and yields more water to a well than the upper part of the aquifer. The upper part of the aquifer, Hell Creek Formation, consists of alternating layers of shale, sandstone, sand, gravel, clay, and lignite (U.S.G.S. 1975). Many of the individual sandy layers are thin and lenticular and do not extend for more than a few miles.

Wells in the Fox Hills-Hell Creek Aquifer generally yield less than 30 gallons per minute. However, in some localities where the sand layers are unusually thick and contain very little interstitial silt or clay, yields may be as much as 150 gallons per minute.

Water quality in the Fox Hills-Hell Creek Aquifer varies markedly, becoming quite saline in the western part of the region. Where the water is potable it is used for rural domestic and stock purposes.

Fort Union Aquifer

Three formations make up the Fort Union Aquifer in the western area of Region 6: the basal Ludlow Formation; the Cannonball Formation; and the Tongue River Formation (U.S.G.S. 1975). The Ludlow Formation and the Tongue River Formation consist of interbedded layers of claystone, sandstone, and lignite which represent sediments deposited under continental conditions. Individual beds in these formations usually cannot be traced for as much as a mile. The middle unit, called the Cannonball Formation, consists of marine shale and sandstone and is traceable over the region. The thickness of the complete Fort Union Aquifer is approximately 1,100 feet near the center of the Williston Basin, and thins toward the east (Reeder 1978).

The quantity of water the Fort Union Aquifer will yield to wells depends on the thickness, sorting, and grain size of the sand beds.

The amount of interstitial silt and clay also influences the amount of water available to a well. Wells commonly are equipped with cylinder pumps and generally have capacities of only two to four gallons per minute. Properly constructed wells finished in sand beds 100 feet thick will yield as much as 50 gallons per minute (Reeder 1978).

Most wells that tap the Fort Union Aquifer are used for rural domestic and stock supplies. Some wells that can produce higher yields are used for small municipal and industrial supplies. In much of the area the water is too saline, high in sodium sulfate, to be used for human consumption.

MAJOR AQUIFERS

The previous sections of this chapter described the basic geologic framework and hydrogeologic framework for Region 6. In these sections the major aquifers of Region 6 were identified and generally described. Table 6-1 provides a listing of the major aquifers in the region.

For the purpose of this study, a major aquifer is identified as an aquifer with significant areal extent that can sustain typical well yields of at least 50 gallons per minute throughout its extent. Some of the major aquifers listed in Table 6-1 do not meet the minimum yield requirement, but are listed because of their widespread use.

Each of the major aquifers were evaluated for ATES potential according to the guidelines established in the Introduction. Data were gathered, stored, and tabulated by computer for those aquifers with apparent ATES potential. Table 6-2 is a computer listing of all data gathered for each aquifer that is believed to have some ATES potential in Region 6.

AQUIFERS UNSUITABLE FOR ATES

All of the major aquifers of Region 6 have been evaluated according to the guidelines established in the Introduction. On the basis of this evaluation many of the aquifers have been judged as generally unsuitable for ATES. In most cases, site-specific studies are needed to more fully evaluate the ATES potential of each aquifer. The aquifers judged at this time as unsuitable for ATES are discussed below, together with the justification for their elimination from further consideration. The aquifers are discussed according to the format established in the Geologic Framework section of this region chapter: 1) Recent alluvium and Pleistocene unconsolidated deposits; 2) eastern and mid-continent Paleozoic rocks; and 3) western plains Late Mesozoic and Cenozoic rocks. Figure 6-5 provides a listing of the major aquifers in Region 6 considered at this time to be unsuitable for ATES.

RECENT ALLUVIUM AND PLEISTOCENE UNCONSOLIDATED DEPOSITS

As established in the Hydrogeologic Framework section of this chapter, the sand and gravel aquifers associated with Recent alluvial deposits are capable of sustaining large yields, in many areas greater than 1,000 gallons per minute. However, the sedimentary depositional environment associated with rivers and streams provides for rapid facies changes. As a result of rapid facies changes, the sand and gravel aquifers are generally not widespread and hydrologic conditions may change markedly over the extent of the aquifer. An alluvial aquifer may be confined in some areas and unconfined in others.

Site-specific studies may establish that alluvial sands and gravels at a particular location are suitable for ATES. However, the regional

AQUIFER	REASONS FOR UNSUITABLE RECOMMENDATIONS	COMMENTS
Localized Alluvial Sand and Gravel	Rapid facies changes make the hydrologic conditions vary place to place; therefore aquifers are sub-regional in extent.	Site-specific studies may provide information that proves an alluvial aquifer is suitable for A.T.E.S. at a particular location.
Pleistocene Unconsolidated Deposits	Rapid facies changes make the hydrologic conditions vary place to place; therefore aquifers are sub-regional in extent.	Site-specific studies may provide information that proves the aquifer is suitable for A.T.E.S. at a particular location.
Pennsylvanian Sandstones	Rapid facies changes make the hydrologic conditions vary place to place; therefore aquifers are sub-regional in extent.	Site-specific studies may provide information that proves the aquifer is suitable for A.T.E.S. at a particular location.
Paleozoic Carbonates and Evaporites	Fracture Porosity	All aquifers with fracture porosities are considered unsuit — able for A.T.E.S. at this time owing to the random and unpredictable volumes of stored water in these aquifers.
Precambrian Crystallines and Metasediments	Fracture Porosity	All aquifers with fracture porosities are considered unsuit — able for A.T.E.S. at this time owing to the random and unpredictable volumes of stored water in these aquifers.
Pierre Shale	Fracture Porosity	All aquifers with fracture porosity are considered unsuit — able for A.T.E.S. at this time owing to the random and unpredictable volumes of stored water in these aquifers.
Fox Hills — Hell Creek Aquifer	Rapid facies changes make the hydrologic conditions vary place to place; therefore aquifers are sub-regional in extent.	Site - specific studies may provide information that proves the aquifer is suitable for A.T.E.S. at a particular location.
Fort Union Aquifer	Rapid facies changes make the hydrologic conditions vary place to place; therefore aquifers are sub-regional in extent.	Site-specific studies may provide information that proves the aquifer is suitable for A.T.E.S. at a particular location.

MAJOR AQUIFERS UNSUITABLE FOR A.T.E.S. IN REGION 6

FIGURE 6-5

scope of this study dictates that in general, these sub-regional aquifers should be eliminated from further consideration.

Many sand and gravel aquifers associated with glacial outwash are also local and not regional in extent. These thin, sub-regional outwash deposits are found in areas along the ice margin of the continental ice masses. These deposits reflect fluctuating climatic conditions as the ice masses advanced and retreated. Where these deposits are confined by till layers, hydrologic conditions may be suitable for ATEs but cannot be predicted prior to site-specific studies.

EASTERN AND MID-CONTINENT PALEOZOIC ROCKS

There are many Pennsylvanian-aged sandstones which yield the minimum requirement of 50 gallons per minute and could be suitable for ATEs. There have been very few data generated for these sandstones, therefore, a qualitative assessment of their suitability must be made. These Pennsylvanian sandstones are alluvial channel sandstones associated with continental deposition and therefore are subregional or local in their extent. The location of these Pennsylvanian sandstones and their water yields cannot be predicted prior to drilling. Even though it may be found that these sandstones are suitable for ATEs at particular localities, owing to the regional scope of this report, these sandstones shall be eliminated from further consideration. Site-specific information should be developed to actually determine whether a Pennsylvanian sandstone at a given locality is suitable for ATEs.

The predominant type of aquifer in the Paleozoic sedimentary rocks of the east and mid-continent is associated with fractures and solution

cavities developed in the carbonates (limestones and dolomites). Aquifers associated with secondary porosities are considered undesirable for ATES because of the somewhat random and unpredictable volumes of stored water in these aquifers. Therefore, the carbonate aquifers associated with the Mississippian, Devonian, Silurian, and Middle Ordovician systems are eliminated from further consideration for ATES.

The evaporite complex of Silurian age in the Michigan Basin is also an aquifer developed from fractures and solution cavities. Also, the aquifers associated with the Precambrian crystalline basement and meta-sedimentary rocks are developed from fracture systems. Following the same logic that determined the carbonate aquifers as unsuitable for ATES, the evaporite aquifers and Precambrian aquifers should be eliminated from further consideration owing to their secondary porosities.

WESTERN PLAINS LATE MESOZOIC AND CENOZOIC ROCKS

The Pierre Shale Aquifer is of regional extent, but the yield of the aquifer is associated with fracture systems developed in the shale. Commonly, the aquifer does not yield the minimum requirement of 50 gallons per minute. In the localities where the aquifer does yield 50 gallons per minute or more, it is because of a well-developed fracture system. Owing to the secondary porosity of the Pierre Shale Aquifer, it should be eliminated from further consideration for ATES.

The Fox Hills-Hell Creek Aquifer and the Fort Union Aquifer commonly have typical well yields far less than the minimum requirement of 50 gallons per minute. Owing to the predominant continental deposition of the sediments associated with these aquifers, the lithologies vary considerably from place to place and are composed of interbedded

sand, clay, silt, and lignite. The sand layers are usually thin and lenticular and do not extend for more than a few miles. In the localities where the sand layers are thick and the amounts of interstitial clay and silt low, typical well yields of these aquifers may be in excess of 50 gallons per minute and conditions favorable for ATES. Site-specific information is needed to make the determination that these two aquifers are suitable for ATES at a given locality. However, on a regional scale, and in accordance with the scope of this project, the Fox Hills-Hell Creek Aquifer and Fort Union Aquifer may be eliminated from further consideration for ATES because typical well yields are generally less than the minimum yield requirement of 50 gallons per minute. Also, because there are rapid facies changes in these two aquifers, the hydrogeologic framework would be difficult to model at a given locality without a detailed site-specific study.

AQUIFERS SUITABLE FOR ATES

Data gathered on aquifers in Region 6 indicate that there are several regional aquifers which may be suitable for ATES. The data provided in Table 6-2 were reviewed with respect to the aquifer evaluation guidelines provided in the Introduction. Based upon the evaluation, an assessment was then made of the type of ATES storage that may be developed from an aquifer: large system chill, low or high temperature storage, or small system chill, low or high temperature storage. The following discussion of suitable aquifers is organized according to the format established in the Geologic Framework and Hydrogeologic Framework sections of this chapter. Figure 6-6 provides a listing of the major aquifers in Region 6 which are suitable for ATES.

RECENT ALLUVIUM AND PLEISTOCENE UNCONSOLIDATED DEPOSITS

Recent Alluvium

Throughout the glaciated central region (Region 6) there are numerous sand and gravel aquifers which may be suitable for ATES. Site-specific information is lacking for most of these aquifers. In general, it is known that widespread sand and gravel aquifers occur at the base of the major stream and river valleys, such as the Missouri, Mississippi, and Ohio. It is recommended that further investigations be made to isolate those areas in these river valleys may be suitable for ATES. One such area, the American Bottoms area of the Mississippi River Valley, has been studied in detail and appears to have ATES potential.

AQUIFER	TYPES OF A.T.E.S. STORGE	COMMENTS
Widespread Alluvial Sands and Gravels	Small system — low or chill storage	Site —specific information is needed to determine where conditions in the aquifers are most suitable for A.T.E.S.
Widespread Outwash Deposits	Large system — low or chill storage	Site —specific information is needed to determine where conditions in the aquifers are most suitable for A.T.E.S.
Cambro-Ordovician and Cambrian Sandstones	Large system — high, low, chill storage	The depth to these aquifers varies markedly over the region. In some areas the aquifers are too deep for an A.T.E.S. facility to be economical.
Dakota Sandstones	Small system — high, low, chill storage Large system — high, low, chill storage	There are insufficient data at this time to make an adequate assessment of all the aquifers' potential for A.T.E.S. It may be found that there are areas of the aquifer which may be suitable for each of the different types of storage.

MAJOR AQUIFERS SUITABLE FOR A.T.E.S. IN REGION 6

FIGURE 6-6

Data for the American Bottoms area of the Mississippi River Valley is provided in Table 6-2. This area of the aquifer is located on the east side of the Mississippi River, across from St. Louis, Missouri. This aquifer is used for municipalities and industries in the area, and extensive research has been conducted to evaluate its capabilities.

The aquifer is composed of two major distinct sand and gravel layers, commonly referred to as the "upper" versus the "lower" aquifer. The "lower" aquifer is usually confined and more widespread than the "upper" aquifer and probably has the greatest potential for ATES (Bergstrom et al. 1968; and Schicht 1965).

Aquifer characteristics, such as thickness, well yield, transmissivity, depth, and hydraulic conductivity, vary markedly over the extent of the aquifer. However, all of the data indicate that these parameters fall within the guidelines as being suitable for ATES (Bergstrom et al. 1968; and Schicht 1965).

The temperature of the water from the American Bottoms aquifer ranges from 11.7° C to 16.7° C (Schicht 1965). Owing to the type of confinement (leaky-aquitard) and the temperature of the water in the aquifer, the aquifer should probably be considered only for small system chill or small system, low temperature storage. There is an apparent risk of breaching the confining layer if large or high temperature storage systems were developed.

Another area where the alluvial sands and gravels indicate ATES potential is near Dayton, Ohio, in the Great Miami River Valley. Data for this aquifer are provided in Table 6-2. There is not as much information on the Great Miami River Valley Alluvium as there are data

available for the American Bottoms Alluvium. Site-specific information should be developed prior to development of an ATES facility.

Geologic information indicates that again the aquifer may be divided into an "upper" versus a "lower" aquifer, separated by a confining layer. Based upon the limited information available, the "lower" aquifer is probably best suited for small chill or low temperature storage to prevent possible breaching of the confining layer (Spieker 1968; and Fidler 1975).

Outwash Deposits

Widespread outwash deposits occur in abandoned river channels, such as the abandoned channel of the Mississippi River and the Teays River which flowed through the Mahomet Valley. The aquifers associated with these sands and gravels appear to have excellent potential for ATES.

The widespread outwash deposited at the base of the abandoned Mississippi River Valley is called the Sankoty Sand (Bergstrom et al. 1968). The southern part of the abandoned valley is now occupied by the Illinois River, and most of the municipalities along the river obtain their drinking water supplies from the Sankoty Sand. There are very few hydrologic data published about the Sankoty Sand Aquifer. The literature indicates the aquifer commonly has a sustained yield in excess of 500 gallons per minute. Geologic information on the Sankoty Sand indicates that the aquifer may be found at depths greater than 200 feet and is usually confined by overlying till units. Site-specific information should be developed prior to an evaluation of the aquifer's suitability for ATES.

Probably the best known and most reliable aquifer associated with an outwash deposit is the Mahomet Sand, found at the base of the buried Mahomet (or Teays) River Valley. The ancient river valley was located by seismic data and has been traced from West Virginia to Illinois. The outwash deposits found in the West Virginia, Ohio and Indiana portions of the valley are fine-grained and well yields are less than 50 gallons per minute (Norris and Spicer 1958). The outwash found at the base of the Mahomet Valley in Illinois, however, becomes coarse-grained and well yields are typically in excess of 1,000 gallons per minute (Visocky and Schicht 1969). Many of the municipalities of Central Illinois derive their drinking water supplies from the Mahomet Sand (Selkregg and Kempton 1958).

Data on the Mahomet Sand Aquifer are provided in Table 6-2. Geologic information indicates that the aquifer is usually confined by overlying till layers. Even though the depth to the top of the aquifer ranges from 30 to 320 feet, the aquifer is typically found at depths greater than 200 feet below land surface. Hydrologic characteristics vary markedly over the extent of the aquifer, but all of the parameters indicate that the aquifer would be suitable for ATEs in certain localities.

A maximum value for transmissivity is given as 510,000 gallons per day per foot. A maximum value for hydraulic conductivity is given as 1,038.5 feet per day (Visocky and Schicht 1969). These values indicate that retrieval of a stored energy mass may be difficult in some areas of the aquifer. However, values for transmissivity and hydraulic conductivity range as low as 3,000 gallons per day per foot and 26.8 feet per day respectively, indicating that there are areas of the aquifer which are suitable for ATEs.

Because of the high well yields and degree of confinement (often overlying till layers are greater than 50 feet thick), areas of the Mahomet Sand aquifer, in general, could be suitable for large system chill or low temperature storage. However, the aquifer should be studied in detail at a given locality before large system high temperature storage is considered.

EAST AND MID-CONTINENT PALEOZOIC ROCKS

Cambro-Ordovician and Cambrian Sandstones

Throughout the east and mid-continent the bedrock aquifers which show the most promise for ATEs are the sandstones of Ordovician and Cambrian age. As described in the Hydrogeologic Framework section, the Lower Ordovician and Upper Cambrian sandstones are commonly grouped together and referred to as the Cambro-Ordovician Aquifer. The sandstones of the Middle and Lower Cambrian are referred to as the Cambrian Aquifer. Table 6-3 is a listing of each of the sandstone units which make up the Cambro-Ordovician and Cambrian Aquifers in the east and the mid-continent areas of Region 6.

Where the water in the Ordovician- and Cambrian-aged sandstones is potable, it is used for drinking water supplies. This is the case in the metropolitan areas of Chicago and Minneapolis-St. Paul. In areas where the water becomes too saline to be potable, the aquifers are commonly used for waste injection. Because the Cambro-Ordovician and Cambrian Aquifers have been widely developed, and owing to the dependency of metropolitan areas upon the aquifers, these aquifers have been widely studied and abundant data have been generated. Table 6-2 provides some of the most reliable data for these aquifers found in the literature.

Scrutiny of the data reveals that the hydrologic and geologic characteristics of the Cambro-Ordovician and Cambrian Aquifers do vary across the extent of the aquifers. However, in general, the aquifers do fall within the guidelines of being suitable for ATEs over most of the area.

Owing to various factors, including: typical well yields in excess of a 1,000 gallons per minute, depth (generally exceeds 1,000 feet), degree of confinement, and aquifer thickness (greater than 100 feet), the Cambro-Ordovician and Cambrian Aquifers appear to be well suited for large system high temperature ATEs facilities. Other aquifer parameters, such as the horizontal versus vertical permeability ratio (Hughes et al. 1966), porosity values, and transmissivity, also indicate that the aquifers are suitable for large system high temperature facilities.

CAMBRO-ORDOVICIAN AQUIFER

<u>East</u>	<u>Mid-Continent</u>
Oswego Sandstone	(Glenwood) St. Peter Sandstone
Theresa Sandstone	Franconia Sandstone
	Iron-ton-Galesville Sandstone
	Jordan Sandstone

CAMBRIAN AQUIFER

<u>East</u>	<u>Mid-Continent</u>
Potsdam Sandstone	Mt. Simon Sandstone
	Dresbach Group Sandstones
	Hinckley Sandstone

Table 6-3

List of Ordovician and Cambrian Sandstones
in the Cambro-Ordovician and Cambrian Aquifers

WESTERN PLAINS LATE MESOZOIC AND CENOZOIC ROCKS

Dakota Sandstone

Throughout the western plains area of Region 6, the bedrock aquifer showing the most promise for ATEs is the Dakota Sandstone Aquifer. As established in the geologic and hydrogeologic sections of this report, the Dakota Sandstone Aquifer is predominantly a widespread marine sand and is commonly confined by overlying units, such as the Pierre Shale.

Even though there is abundant general geologic information available on the Dakota Sandstone Aquifer, specific hydrologic data are difficult to find in the literature. Most of the information found on the Dakota Sandstone Aquifer in Region 6 was information about the aquifer in the state of South Dakota (U.S.G.S. 1975; and Schoon 1971). Table 6-2 provides what limited hydrologic data were available on the Dakota Sandstone Aquifer. Without sufficient hydrologic information, the aquifer's suitability for ATEs was determined by what is known about the geologic conditions of the Dakota Sandstone Aquifer.

The geologic conditions (thickness, depth, lithology) vary markedly over the region. Extensive site-specific information will have to be generated before an adequate, site-specific assessment of the aquifer's suitability for ATEs can be made. Because the geologic conditions of the aquifer vary so dramatically over the region, the hydrologic characteristics of the aquifer should also have tremendous variation over the region. Without adequate information at this time, it is premature to evaluate what type of ATEs facility is feasible for the aquifer. It may be found after further study that there are areas of the aquifer suitable for each of the different types of storage (i.e. large system chill, low or high temperature storage; small system chill, low or high temperature storage).

REGION'S ATES POTENTIAL

Several aquifers in Region 6 show potential for thermal energy storage. The aquifers showing the most promise for ATES are: 1) widespread alluvial aquifers for small system chill or low temperature storage; 2) outwash deposits in buried bedrock valleys (Sankoty Sand and Mahomet Sand) for large system chill or low temperature storage; 3) the Cambro-Ordovician and Cambrian sandstones for large system chill, low or high temperature storage; and 4) the Dakota Sandstone, which has insufficient data available in the literature to make an adequate assessment of ATES potential at this time. In all cases, site-specific information is needed before development of an ATES facility.

Owing to the regional scope of this study, only the regional aquifers of Region 6 were considered for ATES potential, and only the most recent and available literature was reviewed. Site-specific information may possibly prove that aquifers other than those cited above have potential for ATES at particular localities. The purpose of this regional study is to determine the aquifers with the greatest potential for ATES and should not preclude site-specific investigations.

REFERENCES CITED

- Bergstrom, R. E., 1956, Groundwater geology in western Illinois, North Part: Illinois Geol. Survey Circ. 222, 21 p.
- #031 Bergstrom, Et. al., 1968, Ground-water resources of the Quaternary deposits of Illinois: in The Quaternary of Illinois, Univ. of Illinois College of Agriculture Special Publication 14, pp. 157-164.
- Bloyd, R. M., Jr., 1974, Summary appraisals of the nation's ground-water resources - Ohio Region: U. S. Geol. Survey Prof. Paper 813-A, 41 p.
- #032 Borman, R. G., 1976, Ground-water resources and geology of Walworth County, Wisconsin: pub. by University of Wisconsin - Extension Geological and Natural History Survey, Information Circular Number 34, 45 p.
- Cartwright, Keros, 1970, Groundwater discharge in the Illinois Basin as Suggested by Temperature Anomalies: Water Resources Research, vol. 6, no. 3, pp. 912-918.
- Dott, R. H., Jr., and Batten, R. L., 1971, Evolution of the earth: McGraw-Hill Book Company, 649 p.
- #033 Emerich, G. H., 1966, Ironton and Galesville (Cambrian) sandstones in Illinois and adjacent areas: Illinois Geol. Survey Circ. 403, 55 p.
- #034 Fidler, R. E., 1975, Digital Model Simulation of the glacial-outwash aquifer at Dayton, Ohio: U. S. Geol. Survey Water Resources Investigations 18-75, 25 p.
- Geraghty, et. al., 1973, Water atlas of the United States: Water Information Center, Port Washington, New York, 122 Plates.
- #035 Horick, P. J., 1970, Water resources of Iowa: Papers given at a symposium in the geology section of the Iowa Academy of Science at the University of northern Iowa April 18, 1969, University Printing Service, 175 p.
- #036 Hughes, G. M., Kraatz, Paul, and Landon, R. A., 1966, Bedrock Aquifers of Northeastern Illinois: Illinois Geol. Survey Circ. 406, 15 p.
- Norris, S. E., and Fidler, R. E., 1971, Availability of Ground Water from Limestone and Dolomite Aquifers in northwestern Ohio: U. S. Geol. Survey Prof. Paper 750, Part B, 7 p.
- Norris, S. E., and Spicer, H. C., 1958, Geological and geophysical study of the preglacial Teays Valley in west-central Ohio: U. S. Geol. Survey Water-Supply Paper 1460-E, 30 p.
- Prickett, T. A., et. al., 1964, Ground-water development in several areas of Northeastern Illinois: Illinois State Water Survey Report of Investigations 47, 93 p.

REFERENCES CITED (Continued)

- Reeder, H. O., 1978, Summary appraisals of the nation's groundwater resources - Souris-Red-Rainy region: U. S. Geol. Survey Prof. Paper 813-K, 24 p.
- #037 Schicht, R. J., 1965, Ground-water development in East St. Louis, Illinois: Illinois State Water Survey Report of Investigation 51, 70 p.
- #038 Schoon, R. A., 1971, Geology and hydrology of the Dakota Formation in South Dakota: South Dakota Geological Survey, Report of Investigations No. 104, 55 p.
- Selkregg, L. F., and Kempton, J. G., 1958, Groundwater Geology in East-Central Illinois: Illinois Geol. Survey Circ. 248, 36 p.
- #039 Spieker, A. M., 1968, Ground-water hydrology and geology of the lower Great Miami River Valley, Ohio: U. S. Geol. Survey Prof. Paper 605-A, 37 p.
- U. S. Geological Survey, 1975, Mineral and Water Resources of South Dakota: United States Senate Committee on Interior and Insular Affairs, 313 p.
- #040 Visocky, A. P. and Schicht, R. J., 1969, Groundwater resources of the buried Mahomet bedrock valley: Illinois State Water Survey Report of Investigation 62, 52 p.
- #041 Waller, R. M., Turk, J. T., and Dingman, R. J., 1978, Potential effects of deep-well waste disposal in Western New York: U. S. Geol. Survey Prof. Paper 1053, 39 p.

GENERAL REFERENCES

The following references for Region 6 were reviewed but are not cited in the report.

- Becher, A. E., 1978, Ground water in Pennsylvania: Pennsylvania Geological Survey, Educational Series No. 3, 42 p.
- Bergstrom, R. E., and Zeizel, A. J., 1957, Groundwater geology in western Illinois, south part: Illinois Geol. Survey Circ. 232, 28 p.
- Bloyd, R. M., Jr., 1975, Summary appraisals of the nation's ground-water resources - upper Mississippi region: U. S. Geol. Survey Professional Paper 813-B, 22, p.
- Borman, R. G., and Trotta, L. C., 1975, Ground-water resources and geology of Jefferson County, Wisconsin: pub. by University of Wisconsin - Extension Geological and Natural History Survey, Information Circular Number 33, 31 p.
- Cagle, J. W. and Heinitz, A. J. 1978, Water resources of southcentral Iowa: Iowa Geological Survey Water Atlas Number 5, 97 p.
- Heath, R. C., 1964, Ground water in New York: State of New York Conservation Department Water Resources Commission, Bulletin GW-51, Albany, N.Y.
- Horick, P. J., and Steinhilber, W. L., 1973, Mississippian aquifer of Iowa: Iowa Geological Survey, Miscellaneous Map Series 3.
- Huffman, G. C., 1972, Summary of ground-water hydrological data in Michigan in 1972: U. S. Geol. Survey In coop with the Michigan Department of Natural Resources Geological Survey Division, 90 p.
- McGuinness, C. L., 1962, Water in South Dakota: South Dakota State Geological Survey, Water Resources Report No. 2, 33 p.
- Taylor, O. J., 1978, Summary appraisals of the nation's ground-water resources - Missouri Basin region: U. S. Geol. Survey Prof. Paper 813-Q, 41 p.
- University of Nebraska, 1969, Ground water atlas of Nebraska: Conservation and Survey Division, Univ. of Nebraska, 10 p.
- University of Nebraska, 1969, Ground water atlas of Nebraska: Conservation and Survey Division, Univ. of Nebraska, 10 p.
- Walton, W. C., 1953, The hydraulic properties of a dolomite aquifer underlying the village of Ada, Ohio: U. S. Geol. Survey Technical Report No. 1, 31 p.
- Weist, W. G., Jr., 1978, Summary appraisals of the nations ground-water resources - Great Lakes region: U. S. Geol. Survey Prof. Paper 813-J, 29 p.

DISTRIBUTION

No. of
Copies

No. of
Copies

OFFSITE

A. A. Churm
DOE Patent Division
9800 S. Cass Avenue
Argonne, IL 60439

John J. Brogan
DOE Office of Energy
Systems Research
Washington, DC 20585

Arnold Epstein, Project Manager
CR-341, Forrestal Building
DOE
Washington, DC 20585

B. J. Gallagher
DOE Office of Energy
Systems Research
Washington, DC 20585

T. Levinson
DOE Office of Energy
Systems Research
Washington, DC 20585

G. F. Pezdirtz
DOE Office of Energy
Systems Research
Washington, DC 20585

Veronica Rabl
DOE Office of Energy
Systems Research
Washington, DC 20585

S. Strauch
DOE Office of Energy
Systems Research
Washington, DC 20585

J. H. Swisher
DOE Office of Energy
Systems Research
Washington, DC 20585

27 Technical Information Center

Fred J. Molz
School of Engineering
Auburn University
Auburn, AL 36830

5 Jack D. Beemer
Century West Engineering
Corporation
1444 N.W. College Way
P.O. Box 1174
Bend, OR 97701

Donald Langmuir
Department of Chemistry
and Geochemistry
Colorado School of Mines
Golden, CO 80401

Louis Stern
Dames & Moore
6 Commerce Drive
Cranford, NJ 07016

Walter Hausz
4520 Via Vistosa
Santa Barbara, CA 93110

Charles F. Meyer
1141 Cima Linda Lane
Santa Barbara, CA 93108

Chin Fu Tsang
Bldg 90, Room 1012-H
University of California
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720

Victor E. Hampel
Integrated Information Systems
Computation Dept., L-275
University of California
Lawrence Livermore Laboratory
P.O. Box 808
Livermore, CA 94550

No. of
Copies

L. Lorenz
Internorth
2223 Dodge St.
Omaha, NE 68102

Matt Walton
Minnesota Geological Survey
319 15th Avenue S.E.
Minneapolis, MN 55455

R. A. Duscha
NASA Lewis Research Center
21000 Brookpark Blvd.
Cleveland, OH 44135

E. R. Furman
NASA Lewis Research Center
21000 Brookpark Blvd.
Cleveland, OH 44135

A. William Nice
NASA Lewis Research Center
21000 Brookpark Blvd.
Cleveland, OH 44135

National Aeronautics
and Space Administration
Asst Adm for Energy Programs
Washington, DC 20546

National Science Foundation
Division of Advanced Energy
Research and Technology
Room 1140
1800 G Street, NW
Washington, DC 20550

Director
New York State Energy Research
& Development Agency
Rockefeller Plaza
Albany, NY 12223

J. F. Martin
Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37830

No. of
Copies

Douglas D. Huxtable, Director
Energy R&D
Rocket Research Company
York Center
Redmond, WA 98052

L. B. Katter
Rocket Research
York Center
Redmond, WA 98052

L. Radosevich
Sandia Laboratories, Livermore
P.O. Box 969
Livermore, CA 94550

W. G. Wilson
Sandia Laboratories, Livermore
P.O. Box 969
Livermore, CA 94550

Sandia Laboratories
Technical Library Div. 3141
Albuquerque, NM 87185

Frank Baylin
Solar Energy Research Institute
1536 Cole Blvd
Golden, CO 80401

Charles Wyman
Solar Energy Research Institute
1536 Cole Blvd
Golden, CO 80401

Allan Michaels
Solar Thermal Storage Programs
Argonne National Laboratory
Building 362
9700 South Cass Avenue
Argonne, IL 60439

John F. Spencer
Department of Ecology
State of Washington
Olympia, WA 98504

No. of
Copies

J. M. Cherne
TRW
One Space Park
Redondo Beach, CA 90278

Jerry J. Phillips
Projects Manager
Tennessee Valley Authority
350 Commerce Union Bank Bldg
Chattanooga, TN 37401

William Waldrop
Assistant Branch Chief
Water Systems Development Branch
Division of Water Management
Tennessee Valley Authority
P.O. Drawer E
Norris, TN 37828

Craig Cooley
Terra Tek
University Research Park
400 Wakara Way
Salt Lake City, UT 84108

Donald L. Reddell
Agricultural Engineering Dept.
Texas A&M University
College Station, TX 77843

U.S. Army Corps of Engineers
Attn: Library
P.O. Box 59
Louisville, KY 40202

U.S. Department of Energy
Attn: Chief, APMBR
Division of Energy Storage
Systems
Washington, DC 20545

U.S. Department of Energy
Attn: Director, Policy and
Planning
Office of Conservation and
Solar Applications
Washington, DC 20545

No. of
Copies

U.S. Department of Interior
Attn: Natural Resources Library
Serials Branch (G/E)
Washington, DC 20240

Kevin Billings, Legislative Assistant
Office of Congressman Sid Morrison
1330 Longworth Building
Washington, DC 20515

Robert D. MacNish,
District Chief
Arizona District
U.S. Geological Survey
Federal Building
Tucson, AR 85718

Union Carbide Corporation
Nuclear Division
Attn. Library
Y-12 Plant
P.O. Box Y
Oak Ridge, TN 37830

Stanley N. Davis
Department of Hydrology and
Water Research
University of Arizona
Tucson, AZ 85705

W. E. Soderberg
Program Director, ATES
University of Minnesota
Physical Plant Operations
200 Shops Bldg.
319 15th Avenue S.E.
Minneapolis, MN 55455

James W. Crosby III
Geology Department
Washington State University
Pullman, WA 99164

David L. Schreiber, Ph.D., P.E.
Consulting Hydraulic Engineer
P.O. Box 1087
(c/o The Colony)
Coeur d'Alene, ID 83814

No. of
Copies

No. of
Copies

ONSITE

DOE Richland Operations Office

H. E. Ransom

49 Pacific Northwest Laboratory

D. Blahnik
S. M. Brown
D. B. Cearlock
T. J. Doherty
J. R. Eliason
A. F. Gasperino

P. L. Hendrickson
C. T. Kincaid
L. D. Kannberg
W. V. Loscutoff
J. E. Minor
D. A. Myers
J. R. Raymond
R. W. Reilly
W. D. Richmond
L. S. Prater (5)
J. A. Stottlemire
G. E. Wukelic
STES Library (20)
Technical Information (5)
Publishing Coordination (2)