Regional Assessment of Aquifers for Thermal Energy Storage

Volume 2

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REGIONAL ASSESSMENT OF AQUIFERS
FOR THERMAL ENERGY STORAGE

VOLUME 2
REGIONS 7 THROUGH 12

Century West Engineering Corporation
Spokane, Washington

June 1981

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Richland, Washington 99352

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Region 7. Unglaciaded Central Region

REGION 7 - UNGLACIATED CENTRAL REGION

INTRODUCTION

Region 7 encompasses that portion of the continental United States lying immediately beyond the furthest southward advance of the continental glaciers during the Pleistocene Epoch. The western regional boundary has a northwest trend along the eastern flank of the Rocky Mountains. The eastern boundary has a northeast trend along the Appalachian Plateau from southwest Pennsylvania to northwest Alabama. The northern border closely follows the Missouri River through the state of Missouri, and from there, the boundary is defined by the southern terminus of maximum Pleistocene glaciation. Bordered on the south by the Gulf Coastal Plain province, the region is dissected in the central portion by the Central High Plains province (Fenneman 1931). A portion of Region 7 is isolated from the rest of the region, encompassing western Wisconsin, southeastern Minnesota, northeastern Iowa, and the extreme northwest corner of Illinois. This area apparently remained ice-free during episodes of continental glaciation. Because glacial deposits are found only in isolated places in the area, this mid-continent portion of Region 7 is commonly referred to as the "driftless area". The regional outline is shown in Figure 7-1.

The average annual precipitation has a regional trend from the arid and semi-arid western portion of the region to the humid, continental climate of the eastern portion. The western states, within the Rocky Mountain rain shadow, generally receive from 7 to 14 inches of precipitation annually. The precipitation increases significantly in the south central area where the plains of Oklahoma, Texas and Kansas

GENERAL OUTLINE OF REGION 7

FIGURE 7-1

receive 20 to 30 inches of precipitation annually. The region's highest annual precipitation occurs along the Appalachian Plateau where precipitation reaches 30 to 60 inches annually.

There exists a significant problem with saline groundwater (greater than 1,000 milligrams per liter total dissolved solids) throughout the region regardless of the availability of meteoric water for recharge. In the semi-arid western states, the lack of sufficient recharge from precipitation has a role in the saline ground-water problem. However, the eastern states, with much higher amounts of precipitation, also have extensive saline ground-water reservoirs. The saline ground-water problems in Missouri have been linked to the presence of an impermeable shale covering which impedes recharge and inhibits the freshening of saline water by meteoric water (Miller 1971). Other major factors are the presence of connate water in the predominantly marine rock formations, the soluble nature of limestones and dolomites, and the chemical composition of shales and coal beds. Generally, the salinity increases with depth. An exception to this is the presence of fresh water in some Cambrian and Pennsylvanian aged sandstones.

Owing to the salinity problem, the deeper and often higher yielding aquifers are seldom used for irrigation or municipal water supplies. Within Region 7, the use of groundwater for stock and domestic purposes is dominant. This is a result of both land use practices and the low yield character of the region's aquifers. Large yields for municipal and irrigation water supplies are most often obtained from the near-surface aquifers such as the Quaternary-aged alluvial deposits associated with the region's several major rivers.

GEOLOGIC FRAMEWORK

The geology of Region 7 is dominated by the presence of marine sedimentary deposits of vast areal extent and great thicknesses. The largest portion of these marine formations was deposited by vast continental seas during the Paleozoic Era. As the seas advanced and retreated during the Paleozoic Era, the depositional environment changed from deep water limestones and shales to cyclic sequences of near shore shallow water (littoral) shales and sandstones. In a few areas, the sandstone beds are considered to be continental deposits such as the channel sandstone deposits of the Pennsylvanian System (Wilson and Van Couvering 1965; Price, Mull and Kilburn 1962). The Paleozoic-aged rocks are at or near the surface in the east and in the west are overlain by a thickness of Mesozoic-aged rocks which thickens westward. Deposition and erosion throughout the region were controlled largely by the presence of structural basins and archs that developed early in the Paleozoic Era and continued into the Mesozoic Era. These regional structural features are shown on Figure 7-2.

For a more complete discussion of the geologic framework, the region is considered to consist of three separate geologic groups based upon the geologic time scale and the depositional environment of the rock formations. The following three divisions will be used for the geologic framework discussion: 1) Eastern Paleozoic rocks; 2) Western Mesozoic and Cenozoic rocks; 3) Cenozoic unconsolidated deposits.

EASTERN PALEOZOIC ROCKS

The eastern portion of Region 7 is dominated by marine sedimentary rocks deposited during the Paleozoic Era. Throughout the eastern area, rock formations of middle to late Paleozoic age are at or near the

REGIONAL STRUCTURAL FEATURES

FIGURE 7-2

the surface and are covered only by a thin mantle of soil. The dominant rock type is limestone, ranging in age from Cambrian to Pennsylvanian.

Throughout the early Paleozoic Era, the continental seas covered much of Region 7 and deposited great thicknesses of deep water limestones, dolomites, and shales. As the seas retreated, a period of non-deposition occurred during the Silurian Period. This is evidenced by the absence of Silurian-aged deposits. Continued marine deposition is indicated by the extensive deposits of shallow water shale that were laid down during the Devonian Period; this shale sequence is known as the Chattanooga Shale and was deposited during the Devonian Period and the Early Mississippian Period.

The Paleozoic Era continued with marine deposition, chiefly limestones and dolomites, during the Mississippian Period. At the close of the Mississippian Period, extensive uplifting took place and resulted in a period of erosion during the Late Pennsylvanian Period. The Mississippian-aged rocks were eroded into a mature surface with great topographic relief. Stream channels estimated at 400-foot depth existed by the Middle Pennsylvanian period (Davis, Plebuch and Whitman 1974). Sandstones of Pennsylvanian age were deposited in these channels and, as the seas advanced again, interbeds of limestone and shale were deposited. Gradually, the channel sandstone deposits were replaced by deltaic and barrier bar deposits together with cyclical deposits of shale, coal, and limestone. These cyclical deposits are the results of continual transgressing and regressing of the sea over a shallow continental surface. Much of the United States coal is deposited

in formations of this type and age. At the close of the Pennsylvanian Period, uplifting had raised much of this area above the continental seas.

The bedrock of the "driftless area" in Region 7 is composed of Paleozoic sedimentary rocks which 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 Paleozoic time. The outcrop of the Paleozoic rocks trends from Upper Ordovician shales to predominantly Middle Ordovician carbonates in the west and southwest portion of the "driftless area", to predominantly sandstones of Early Ordovician and Cambrian age, to Precambrian crystalline rocks of the Canadian Shield exposed in Wisconsin in the northern portion of the driftless area.

The thickness of the Paleozoic sedimentary rocks varies over the area. The Upper Ordovician shales are as much as 400 to 500 feet thick; the Middle Ordovician carbonates are as much as 500 feet thick; and the Lower Ordovician and Cambrian sandstones are from 1,200 to 1,500 feet thick.

The eastern part of the region does not contain rocks deposited during the Mesozoic Era. Although rocks may have been deposited during the Permian Period and into the Mesozoic Era, they were later removed by erosion. The Pennsylvanian-aged deposits are overlain by alluvium and other Quaternary-aged deposits. The close of the Paleozoic Era is represented by a sequence of Permian-aged rocks in south central Oklahoma deposited in the Anadarko Basin. These rocks are known as the Hennessey Group, El Reno Group, and White Horse Group (Tanaka and Davis 1963; Hart 1974).

WESTERN MESOZOIC AND CENOZOIC ROCKS

This division of the geologic framework includes over three-quarters of the region and well over one-half of the geologic record. For the purpose of this discussion, the western part of the region is considered to lie west of Missouri and Arkansas. The geologic record of the post-Paleozoic Era in this area can best be discussed by considering three depositional periods. The following discussion is presented in three divisions consisting of: 1) Mid-continent transition; 2) Cretaceous period sedimentation; 3) Eastern foothills of the Rocky Mountains.

Mid-Continent Transition

The Mesozoic Era began with the Triassic Period, for which there is an almost complete lack of geologic record. During this time, there were no epeiric seas and the North American continent was a land mass. Not until mid to late Jurassic time did the seas return. The states of Kansas, Oklahoma, and Texas are essentially void of Triassic and Jurassic age rocks. These lower Mesozoic rocks are found along the southern Rocky Mountains and in the Colorado Plateau where they are represented by the continental red bed deposits. The Dockum Group is present in the far west side of Texas and the southeast corner of New Mexico, and contains continental red beds consisting of sandstones, shales, and some limestone from the final stages of a regressing sea (Garza, Sergio and Wesselman 1962). The Spearfish Formation of Middle Triassic age represents the earliest Mesozoic-aged sediments in the northwest part of the region (U.S.G.S. 1975). In the western portion of Kansas, there are some Middle Jurassic-aged sediments present.

For most of Region 7, the transition from rocks of the Paleozoic Era to rocks of the Mesozoic Era takes place in the Late Jurassic and

Early Cretaceous Periods. An advancing sea (Zuni Sea) during the Late Jurassic Period began depositing shallow water sandstones, siltstones, and shales in the western states. The present record of Late Jurassic-aged deposits begins approximately in central Kansas and extends to the northwest. These rocks comprise the Sundance and Morrison Formations common to the furthest western states of the region. The Mesozoic record in the states of Kansas, Texas, and Oklahoma actually begins at the unconformable contact between the Paleozoic-aged rocks and the overlying rocks of the Lower Cretaceous System. These rocks are represented by the alternating sandstones and shale sequences of the Trinity Group, the Fredericksburg Group, and the Washita Group in central Texas and Oklahoma (Leggat 1957; Baker 1960). In Kansas, the Lower Cretaceous rock sequences are represented by the continental Cheyenne Sandstone (lower formation), the marine shales of the Kiowa Formation (middle) and the littoral Dakota Formation. These rocks also represent the gradual transition from predominantly marine deposition to marine and continental deposition common to the Cretaceous Period (Keene and Bayne 1977).

Cretaceous Period Sedimentation

The relatively thin Lower Cretaceous deposits rapidly thicken toward the west and northwest. The extensive deposition during the Cretaceous Period resulted from the continued transgressions of the Zuni Sea which began in the Late Jurassic Period. Then the sea receded in the Early Cretaceous Period and peaked at the close of the Mesozoic Era (Late Cretaceous).

The deposits of Cretaceous age in Texas, Oklahoma, and Kansas are generally more limey than those of Wyoming, Montana, and South Dakota. The Cretaceous-aged deposits of these states generally contain

more clastic material. This is true of the Woodbine Formation, the Eagle Ford Shale, and Austin Chalk in Texas and Oklahoma. In central Kansas, the Colorado Group contains the Greenhorn Limestone Formation with the Jetmore Chalk Member; the Colorado Shale contains the Fairport Chalk Member and the Niobrara Chalk Formation also exists in Kansas. The Colorado Group, the Montana Group, and the Inyan Kara Group of Cretaceous age in Wyoming, Montana, and South Dakota, all consist predominantly of shales with interbedded sandstones and very minor limestone beds. The uppermost Cretaceous sequence, known as the Fox Hills Sandstone and the Hell Creek Formation (Lance Formation in Wyoming), are non-marine sequences of sandstones with interbedded shale and coal.

Eastern Foothills of the Rocky Mountains

The portion of Region 7 that borders the eastern foothills of the Rocky Mountains contains rock formations at or near the surface ranging in age from early Paleozoic to Tertiary. Owing to the low angle thrust faulting associated with the Late Cretaceous to early Tertiary Laramide Orogeny, the Paleozoic Era rock formations outcrop in this area.

The Paleozoic-aged rock formations present in this area of Region 7 are predominantly marine deposits of limestone and dolomite with interbedded shale and sandstone. These rock formations include the Cambrian-aged Flathead Sandstone; the Gros Ventre and Gallatin Formations; the Bighorn Dolomite of Cambrian and Ordovician age; the Mississippian-aged Madison or Guernsey Limestone; and the Pennsylvanian-aged sandstone of the Amsden and Tensleep Formations. The

Silurian Period is not represented in the geologic record. In most of Colorado, both the Silurian- and the Devonian-aged rocks are not present. The Paleozoic-aged rocks outcrop in a narrow band along the foothills of the Rocky Mountains. Within Region 7, a typical outcrop area is parallel to the Bighorn Mountains of Wyoming.

The faulting, which brought these rocks near the surface, is also responsible for their steep dip, which leaves the Paleozoic-aged rock formations deeply buried throughout much of this area. Their presence is known mainly from their outcrop area and from the logs of deep oil wells. The greatest depth is commonly in the central part of the Powder River Basin in northeast Wyoming and southeastern Montana. The Powder River Basin is an elongated, asymmetrical sedimentary basin with the deepest part on the west side, parallel to the Bighorn Mountains. In this area, the top of the Mississippian-aged Madison Limestone is 15,000 feet below land surface and the Precambrian bedrock is approximately 21,000 feet deeper than on the flanks of the nearby Bighorn Mountains.

As shown on the stratigraphic correlation chart of Figure 7-3, the Powder River Basin also contains extensive deposits of Mesozoic-aged sediments. This stratigraphic correlation chart, together with the stratigraphic chart of Figure 7-4 and Figure 7-5, also shows the difficulty in discussing various rock formations on a regional basis. Often, the rock formations change name at a state boundary or the formation is named and defined by a certain type of section which is not exactly the same elsewhere; therefore, new formation names or subdivisions are created. Within the eastern foothills of the Rocky Mountains, the lower Mesozoic-aged rocks remain fairly consistent in nomenclature. Additional

formation names are found for the lower Mesozoic rocks in the states of Colorado and New Mexico. This is because the lower Mesozoic sequences are dominant in these two states.

The greatest diversity in stratigraphic nomenclature is found in the Cretaceous-aged rock formations. The sedimentary deposits of the Early Cretaceous Period are predominantly marine shale with interbedded sandstone. Typical formations are shown on the chart of Figures 7-3, 7-4 and 7-5. In central Montana, the Early Cretaceous rock formations contain increasing amounts of sandstone and some conglomerate deposits. This is represented by the Kootenai Formation, the Lakota Sandstone, by thick sandstone beds in the Colorado Shale, and by the Eagle Creek Sandstone (Groff 1962; Osterkamp 1968).

The Upper Cretaceous geologic record contains an increasing amount of sandstone and clastic deposits of both marine and non-marine deposition. Owing to the adjacent orogenic activity (Laramide Orogeny), the eastern foothills of the Rocky Mountains contain extensive deposits of Upper Cretaceous age which are predominantly sandstone with interbedded coal and shale. This is a significant change from the predominantly marine shales and interbedded sandstones of the Lower Cretaceous System. The rock formations deposited in the Upper Cretaceous System are conformable with those deposited at the start of the Cenozoic Era during the Paleocene Epoch of the Tertiary Period.

Throughout northeast Wyoming, southeast Montana, northwest South Dakota, and southwest North Dakota, the dominant near surface deposits are the Pierre Shale, the Fox Hills Sandstone, the Hell Creek Formation (Lance Formation in Wyoming), and the Tertiary-aged Fort

GENERALIZED CORRELATION CHART							
ERA	PERIOD	WYOMING		BLACK HILLS AREA			
CENEZOIC	QUATERNARY	ALLUVIUM & TERRACE GRAVELS		Sands and Gravels			
	TERTIARY	PLIOCENE	<div></div>		<div></div>		
		MIOCENE	ARIKAREE		<div></div>		
		OLIGOCENE	WHITE RIVER		WHITE RIVER		
		EOCENE	WASATCH	MONCIEF	<div></div>		
				KINGSBURY Cgl.	<div></div>		
PALEOCENE	FORT UNION	TONGUE RIVER	<div></div>				
		LEBO SH.	<div></div>				
		TULLOCK	<div></div>				
MESOZOIC	CRETACEOUS	LANCE	HELL CREEK	<div></div>			
		MONTANA GR.	FOX HILLS SS.	<div></div>			
			PIERRE SH.	LEWIS SH.	<div></div>		
				TEAPOT SS.	<div></div>		
				MESAVERDE	<div></div>		
				PARKMAN SS	<div></div>		
				STEELE SH.	SHANNON SS	<div></div>	
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STRATIGRAPHIC CORRELATION CHART
FOR THE POWDER RIVER BASIN - BLACK HILLS AREA

(FROM MANCINI, 1976)
FIGURE 7-3

ROCK UNITS										
UNITED STATES GEOLOGICAL SURVEY NOMENCLATURE					MAXIMUM THICKNESS (FEET)	SOUTH DAKOTA GEOLOGICAL SURVEY NOMENCLATURE				
						BLACK HILLS AREA		OTHER AREAS		
CRETACEOUS	Upper Cretaceous	Hell Creek Formation			400	Hell Creek Formation				
			Fox Hills Sandstone				400	Fox Hills Formation	White Owl Creek Member	Colgate Sandstone Member
		Pierre Shale				3000	Pierre Shale		Fortpoint Member	Bullhead Member
					Timber Lake Member					
					Trail City Member					
			Elk Butte Member		Elk Butte Member					
			Moberg Member		Moberg Member					
			Virgin Creek Member		Virgin Creek Member					
			Verendrye Member		Verendrye Member					
			DeGray Member		DeGray Member					
	Crow Creek Member		Crow Creek Member							
	Colorado Group	Niobrara Formation			220	Niobrara Formation				
		Carlile Shale	Sage Breaks Member		550	Carlile Shale	Sage Breaks Member			
			Turner Sandy Member				Turner Sandy Member			
			Pool Creek Shale Member				Pool Creek Shale Member	Cedell Sandstone Mem.		
		Greenhorn Formation	Orman Lake Limestone Member		360	Greenhorn Limestone	Orman Lake Limestone Member			
		Selle Fourche Shale			450	Graneros Shale	Dakota Sandstone	Selle Fourche Shale Member	"D sand"	
		Mowry Shale			250			Mowry Shale Member		
		Newcastle Sandstone			100			Newcastle Sandstone Member	"J sand"	
		Skull Creek Shale			250			Skull Creek Shale Member		
		Lower Cretaceous	Fall River Formation	Keyhole Sandstone Member		150	Fall River Formation	Keyhole Sandstone Member		
	Fuson Member			550	Lakota Formation	Fuson Member				
	Lakota Formation		Minnewaste Limestone Member			Minnewaste Limestone Member				
			Chilson Member			Chilson Member				
	Morrison Formation				350	Morrison Formation				
			Unkpapa Sandstone				Unkpapa Sandstone Member			
Sundance Formation			Redwater Shale Member				740	Sundance Formation	Redwater Shale Member	Swift Member
			Pine Butte Member						Lak Member	Riarden Member
			Lak Member						Hulett Sandstone Mem.	
	Hulett Sandstone Mem.		Stockade Beaver Shale Member							
Canyon Springs Sandstone Member			Canyon Springs Sandstone Member							
Middle Jurassic	Piper Formation ¹			125	Gypsum Spring Formation	Piper Formation ²				
	Gypsum Spring Formation			200						
	TRI-ASSIC	Spearfish Formation			350	Spearfish Formation				

¹ Recognized in eastern South Dakota

² Recognized in northwestern South Dakota

STRATIGRAPHIC NOMENCLATURE OF SOUTH DAKOTA

(FROM U.S.G.S., 1975)

FIGURE 7-4

			Rock unit		Maximum thickness (feet)	Age estimates commonly used for boundaries (in million years)	
CENOZOIC	Quaternary	Holocene	Stream and lake sediments			1.5-2	
		Pleistocene	Glacial deposits and stream and lake sediments		800		
	Tertiary	Pliocene	Ogallala Formation		300	ca. 7	
		Miocene	Batesland Formation		60		
			Rosebud Formation		250		
			Arikaree Group	Harrison Formation		600	
				Monroe Creek Formation			
				Sharps Formation			
		Oligocene	White River Group	Brule Formation		600	26 (Oligocene)
				Chadron Formation			-38 (Eocene)
		Paleocene	Fort Union Group	Tongue River Formation		Eocene intrusive rocks	-54 (Paleocene)
				Cannonball Formation			
				Ludlow Formation			
MESOZOIC	Cretaceous	Upper	Hell Creek Formation		400	136	
			Montana Group	Fox Hills Formation			400
				Pierre Shale			3000
			Colorado Group	Niobrara Formation			220
				Carlisle Shale			550
				Greenhorn Limestone			360
		Belle Fourche Shale		450			
		Lower	Mowry Shale		250		
			Newcastle Sandstone		100		
			Skull Creek Shale		250		
			Inyan Kara Group	Fall River Formation			150
				Lakota Formation			550
	Jurassic		Upper	Morrison Formation		350	
		Sundance Formation		740			
		Middle	Piper Formation		125		
			Gypsum Spring Formation		200		
	Triassic		Spearfish Formation		775	190-195	
	PALEOZOIC	Permian		Minnekahta Limestone		40	225
				Opeche Shale		125	
Pennsylvanian		Minnelusa Formation		1400	280		
Mississippian		(Big Snowy Group)	Kibbey Sandstone		100	320	
			(Charles Formation)		550		
		(Madison Group)	Mission Canyon Limestone		Pahasapa Limestone	1300	
			Lodgepole Limestone				
Devonian		Englewood Formation		70	345		
		(Three Forks Shale)		600			
		(Bird Bear Formation)					
		(Duperow Formation)					
		(Souris River Formation)					
Silurian		(Interlake Group)			395		
Ordovician		(Bighorn Group)	Stony Mountain Formation		600	430-440	
			(Red River Formation) or Whitewood Dolomite				
	Winnipeg Formation		180				
Cambrian	Deadwood Formation		600	ca. 500			
	Sioux Quartzite		5000	570			
PRECAMBRIAN			Metasediments, metavolcanics, metagabbro, granite, and granite gneiss where exposed. Largely granite and granite gneiss in subsurface. Formation names in use apply only to small areas		At least 60,000	3000	

STRATIGRAPHIC NOMENCLATURE OF MESOZOIC ERA IN SOUTH DAKOTA

(FROM U.S.G.S. 1975)

FIGURE 7-5

Union Formation. These formations have been extensively studied for their coal and water resources. When found together, they often exceed a thickness of more than 1,000 feet.

Other Tertiary-aged deposits found throughout the eastern foothills area of the Rocky Mountains are the Eocene-aged Wasatch Formation, the Oligocene-aged White River Formation (or White River Group) and the Miocene-aged Arikaree Formation. The White River Group consists of the lower Chadron Formation and the Brule Formation (U.S.G.S. 1975; Crist and Lowry 1972; Whitcomb 1965). Often, these Tertiary-aged sediments have a combined thickness exceeding 1,000 feet.

CENOZOIC UNCONSOLIDATED DEPOSITS

The Quaternary to Recent deposits of unconsolidated soil and rocks include river alluvial and terrace deposits, landslides, fluvial and colluvial fans, and aeolian (dune) deposits. Occasionally, the river terrace deposits are of late Tertiary age.

The distribution of these deposits is fairly uniform throughout the region. The most important unconsolidated deposits are the river alluvium. Region 7 contains at least a part of all the major United States rivers excluding the Columbia and the Snake Rivers. The major rivers often have extensive channel and flood plain deposits and are responsible for much of the local topography. Of primary importance is the ability of the river alluvium to yield large volumes of good quality water. The hydrogeologic characteristics of the alluvium and other rock formations are discussed in the following section.

HYDROGEOLOGIC FRAMEWORK

Groundwater and the occurrence of water-yielding rock formations often follow a natural grouping which is related to the geologic depositional environment and water-yielding characteristics of a particular group of rock formations. Frequently, the similarities between the depositional environment and water-yielding characteristics lead to a similarity in the chemical characteristics of the water (Crist and Lowry 1972).

Within Region 7, the occurrence of groundwater and other hydrogeologic properties fits into five general divisions or hydrogeologic environments. Based chiefly upon the geologic time scale and secondly upon depositional environment, the five hydrogeologic environments are as follows: 1) Cenozoic unconsolidated deposits; 2) Tertiary deposits; 3) Cretaceous marine sediments; 4) lower Mesozoic sediments; 5) Paleozoic sediments. These classifications are general; therefore, in discussing the hydrogeologic framework, subdivisions are included to indicate specific periods of geologic time and important depositional changes. The five hydrogeological environments listed above are used throughout this report and are considered to contain the major aquifers of the region.

CENOZOIC UNCONSOLIDATED DEPOSITS

The Cenozoic-aged deposits of unconsolidated materials include those deposits discussed in the preceding geologic framework section of this chapter. Deposits of Cenozoic age include both deep alluvial deposits and terrace deposits of late Tertiary age and Quaternary age. Often, large portions of the unconsolidated deposits lie above the local

water table and, therefore, have a smaller role in the hydrogeologic environment than that of the saturated deposits. Those deposits lying above the water table and covering the bedrock of Region 7 are a vital link in the recharge mechanism. The two major means of recharge are from stream flow loss over bedrock and from precipitation upon the land surface. The permeability of the unconsolidated deposits often determines the amount of recharge reaching the underlying aquifers.

The saturated unconsolidated deposits have a much larger role in the hydrogeologic environment. Quaternary-aged alluvium and some deep Tertiary-aged alluvium (Garza, Sergio and Wesselman 1962) are major aquifers throughout the region. Groundwater in these aquifers is under water table conditions and is often hydrologically connected to their associated rivers. Data have been tabulated (Table 7-2) for the alluvium of the Arkansas River, Kansas River, Ohio River, Republic River, and for the valley fill alluvium of a few smaller streams. Other major rivers with alluvial aquifers with similar characteristics are the Mississippi River, the Missouri River, the Rio Grande River, and several intermediate-size rivers in Montana, Wyoming, and Colorado. Owing to the general similarity of alluvial aquifers, data are not tabulated for all the major rivers.

The terraced alluvial deposits contain large thicknesses of permeable sand and gravel, but are often above the local water table. Since a large part of the permeable terraced deposits are drained, they are not as hydrologically significant as the saturated river alluvium. Other deposits of lesser hydrologic significance are the Quaternary glacial deposits. By definition, this region is identified by the absence

of glacial deposits. However, in many places along the region's northern border, the deposits in the channels of the Missouri and Ohio Rivers include some glacial-derived materials. Such deposits are not discussed in this chapter.

TERTIARY DEPOSITS

The Tertiary-aged sedimentary deposits are found in the western portion of Region 7. The major deposits occur in North Dakota, South Dakota, Montana, Wyoming, Colorado, and New Mexico. These deposits are the major near surface formations in the western states and are used extensively for both their coal and ground-water resources.

A large portion of the Tertiary sedimentary deposits have an origin directly related to the Laramide Orogeny. During the Late Cretaceous Period and into the Eocene Epoch of the Tertiary Period, the faulting, uplifting, and associated orogenic activity exposed many rock formations to weathering. Subsequently, extensive deposits of the resulting sediments accumulated in the adjacent basins. Uplifting continued during the Eocene Epoch, and in much of Colorado and New Mexico the lower Tertiary sediments were eroded away (Voegeli and Hershey 1965; Maberry and Hampton 1972).

Extensive aquifers with great areal extent are found in the lower Tertiary sediments. Since the Tertiary-aged rocks conformably overlie the uppermost Cretaceous-aged rock formations of the western states and have a similar depositional environment (orogenic), they often contain a continuous aquifer system. This is particularly true for the Fox Hills and Hell Creek Formations, which are considered to contain

the basal Fox Hills-Hell Creek Aquifer (Taylor 1968; Miller 1979). The lower part of the Fort Union and the upper Hell Creek Formation is another common aquifer in the central Powder River Basin of southeastern Montana (Miller 1979). The two aquifers mentioned above are extensively used throughout southeast Montana, northeast Wyoming, northwestern South Dakota, and southwestern North Dakota. Well yields are consistently below 50 gallons per minute and often range from 20 to 25 gallons per minute (Miller 1979; Hodson, Pearl and Druse 1973; Howells 1979). In east central Colorado, a similar aquifer, the Laramie-Fox Hills Aquifer, yields from 50 200 gallons per minute but is deeply buried at depths of nearly 2,000 feet below land surface (Maberry and Hampton 1972).

In some areas of South Dakota, the Tertiary-aged Fort Union Formation is not used as an aquifer (Howells 1979). The Fort Union Formation in the far northeast part of Wyoming also has very low yields; often the average yield is only 10 gallons per minute (Whitcomb and Morris 1968). Along the western side of the Powder River Basin, an aquifer system in the Fort Union Formation and Lance Formation (Hell Creek equivalent) yields water to many wells and is commonly artesian. In this area, the yields are low (less than 20 gallons per minute), but flowing wells discharging up to 60 gallons per minute have been reported (Whitcomb, Cummings and McCullough 1966). Often, the Fort Union Formation, Lance Formation, Fox Hills and Hell Creek Formations have locally high yields owing to the secondary porosity of the coal beds and associated overlying clinker beds. These formations are not considered major aquifers because of their generally low yields and variable lithology.

The Eocene-aged Wasatch Formation conformably overlies the Fort Union Formation east of the Powder River Basin, but is unconformable along the western side of the basin. In southeastern Montana it is only present in a limited area near the Montana-Wyoming state line (Northern Great Plains Resource Ground-Water Subgroup 1974). Within northeastern Wyoming, the Wasatch Formation is a primary source of ground-water with yields commonly from 10 to 50 gallons per minute and an average well depth of approximately 280 feet below land surface. The yields generally increase in the southwestern part of the Powder River Basin (Whitcomb, Cummings and McCullough 1966). The Wasatch Formation is considered a major aquifer and data are presented in Table 7-2.

The Oligocene-aged White River Group unconformably overlies the Wasatch Formation in Wyoming and the Fort Union Formation in Montana and South Dakota. It is also unconformable with the Golden Valley Formation in southwestern North Dakota (Northern Great Plains Resource Ground-Water Subgroup 1974). This group is recognized as far south as northern Colorado (Weist 1965-B). The White River Group consists of two formations; the upper formation is known as the Brule Formation and the lower, the Chadron Formation. Both formations contain appreciable amounts of volcanic material common to the post orogenic deposits. The water-yielding character varies, and generally yields of approximately 50 gallons per minute are obtained locally from a basal channel deposit. The channel sandstone and conglomerate were deposited upon the eroded surface of the underlying rock formations and are not regionally continuous. In other areas, the White River Group has been shown to contain fine-grained material and is not a major aquifer (Crist and Lowry 1972).

The Miocene-aged Arikaree Formation conformably overlies the White River Group and is found in southeastern Montana, western South Dakota, southwest North Dakota, Wyoming and north central Colorado. This formation is a common aquifer in most areas and is a primary source of groundwater as far east as south central South Dakota (Ellis and Adolphson 1971). Well yields for this formation are less variable than well yields of previously mentioned formations, and yields generally are greater than 100 gallons per minute (Crist 1977; Whitcomb 1965). The Arikaree is considered a major aquifer of Region 7 and is discussed later in this chapter. The data presented in Table 7-2 for this aquifer are from a well-studied area in east central Wyoming.

Other Tertiary-aged deposits with favorable water-yielding characteristics are found in the late Tertiary (Miocene-Pliocene) aged volcanic deposits of southern Colorado and New Mexico. One such deposit, the Santa Fe Group, common to the Pajarito Plateau near Los Alamos, New Mexico, has sufficient data to be contained in Table 7-2 as a major aquifer and is discussed later in this chapter. The high yield from wells tapping this formation, up to 1,400 gallons per minute, can be attributed to a great thickness of volcanic debris and conglomerates that the wells penetrate (Cushman 1965; Purtymun and Cooper 1969).

The Pliocene-aged Ogallala Formation contains extensive water-yielding strata along the northwestern and central borders of Region 7. The Ogallala Formation is found wherever Region 7 borders Region 5 and does not have a significant areal extent within Region 7. The Ogallala Formation was discussed as a major aquifer in Region 5 and is not discussed in this chapter.

CRETACEOUS MARINE SEDIMENTS

The sedimentary deposits of the Cretaceous Period are predominantly marine shales and limestones with interbedded sandstones. The earliest deposits in the Cretaceous Period are often littoral (near shore) to continental sandstones followed by thick shale and limestone deposits which have higher lime content in the south central states of the region. The northern and western states of the region generally have a higher percentage of clastic sediments (shale, siltstone, sandstone).

Early Cretaceous-aged deposits of Texas and Oklahoma are represented by the Trinity Group (oldest), the Fredricksberg Group, the Washita Group, and various individual formations of shale and limestones. The main water-yielding formations are the Travis Peak Formation and Paluxy Sandstone of the Trinity Group, and the Edwards and associated limestones of the Fredericksberg Group (Leggat 1957; Hart 1974; Schoff 1955). The limestone formations commonly have the highest yields owing to their high secondary porosity; however, the yield often cannot be predicted at a given locality. The Trinity Group is considered a major aquifer of Region 7. The sandstone beds of this group are from 140 to 190 feet thick and vary in depth from outcrop to 1,400 feet deep for the Travis Peak Formation and a maximum depth of 900 feet below land surface for the Paluxy Sandstone. The Lower Cretaceous formations have a regional southeastward dip of approximately 33 feet per mile which is locally steepened by the Preston Anticline and the Sherman Syncline in northeast Texas near the Oklahoma border (Baker 1960). The Trinity Group extends into north central Texas near Fort Worth. The sandstone formations grade extends into the Glen Rose Limestone south of the Dallas-Fort Worth area and into south central

Texas (Leggat 1957). In Oklahoma, the Trinity Group equivalent is the Antlers Sandstone, which is a major aquifer in south central Oklahoma (Hart 1974). Data for the sandstone formations of the Trinity Group are contained in Table 7-2 under the Cretaceous marine aquifer section, and the aquifer is discussed in more detail in subsequent sections of this chapter.

The Lower Cretaceous rock formations of central Kansas contain two aquifers, the Cheyenne Sandstone and the Dakota Formation, separated by the relatively impermeable Kiowa Shale. Both aquifers yield to artesian wells and often flow at rates from 25 to 75 gallons per minute (Keene and Bayne 1977). Well yields exceeding 1,000 gallons per minute are common from a properly constructed well penetrating both formations. The Cheyenne Formation is considered to have sandstone beds with a greater areal extent than the Dakota Formation, but owing to the underlying eroded surface, the thickness of a sandstone bed may vary markedly over a short distance. Other factors contributing to the relatively large yields of wells tapping the Cheyenne Formation are the uniformity of grain size and the loose cementation of the sand.

In the remaining western states, the rock formations deposited during the Early Cretaceous Period contain thick sequences of relatively impermeable shales interbedded with sandstone and limestone. Typical formations are shown on Figure 7-3 and Figure 7-4. The Inyan Kara Group and the Colorado Group both contain extensive shale deposits such as the Graneros Shale Formation.

The division between the Lower and Upper Cretaceous Systems is not clear on a regional basis. The Kansas Geological Survey stated

that the division should occur somewhere in the Dakota Formation (McNellis 1973). However, the Dakota Formation and its western equivalent, the Newcastle Sandstone (Schoon 1971) are shown in different time-stratigraphic positions in Figure 7-3 and Figure 7-4. Regardless of the Dakota Formation's stratigraphic position, it is considered a major aquifer of Region 7. The sandstone beds of the Dakota Formation are artesian aquifers throughout Kansas, southeastern Colorado (Voegeli and Hershey 1965), and South Dakota (Schoon 1971; U.S.G.S. 1975). Specific data for the hydrogeologic characteristics of the Dakota Formation are scarce but the data from one source (Schoon 1971) are presented in Table 7-2. The Dakota Formation is discussed in more detail in a subsequent section of this chapter. The rock formations deposited during the Late Cretaceous Period also contain marine shale deposits characterized by the Pierre Shale.

In north central Texas, the Upper Cretaceous System contains the Woodbine Formation which yields moderate to large volumes of water (a maximum of 600 gallons per minute) (Baker 1960). In south central Oklahoma, the Woodbine Formation yields only small volumes of groundwater and is not considered a major aquifer (Hart 1974). For the purpose of this study, the sandstone beds of the Woodbine Formation are considered major aquifers owing to their areal extent throughout central Texas and yields commonly more than 50 gallons per minute. Data for the Woodbine Formation are presented in Table 7-2 and the aquifer is discussed in a subsequent section of this chapter.

LOWER MESOZOIC SEDIMENTS

The sedimentary deposits of the lower Mesozoic Era include rock formations deposited during the Triassic and Jurassic Periods. In

general, rock formations of this age are absent from the eastern part of Region 7 and rarely present in central Texas, Oklahoma, and Kansas. Triassic- and Jurassic-age rock formations are most common in the Colorado Plateau, southeast Colorado, and New Mexico. They are generally found at great depths in Montana, Wyoming, North Dakota, and South Dakota, where the typical formations are the Spearfish or Chugwater Formation (Triassic) and the Piper Formation, Gypsum Springs Formation, Sundance and Morrison Formations of Jurassic age.

Lower Mesozoic-aged deposits are generally continental sandstones, fine-grained, moderately to highly indurated and very seldom yield greater than 10 gallons per minute to well (Berkstresser and Mourant 1966; Miller 1979; Mourant and Shomaker 1970; U.S.G.S. 1975). Exceptions to this are found in the sandstone beds of the Dockum Group of Late Triassic age. The Dockum Group contains the Santa Rosa Formation consisting of sandstone with interbedded clay, shale and conglomerate. This formation is an aquifer in east central New Mexico (Berkstresser and Mourant 1966) where well yields from 1 to 50 gallons per minute are common and springs from the formation flow at rates up to 150 gallons per minute. In the southeast corner of New Mexico and into west Texas, the Santa Rosa Formation is an important aquifer which yields between 160 to 400 gallons per minute from depths generally less than 600 feet below land surface (Garza Sergio and Wesselman 1962). Based upon its areal extent and yield, the Santa Rosa Sandstone of the Dockum Group is considered a major aquifer of Region 7. This formation is probably representative of aquifers in the lower Mesozoic-aged sedimentary deposits. Further discussion of the Santa Rosa Formation and its hydrogeologic properties is presented in a

subsequent section of this chapter. Aquifer data are presented in Table 7-2.

PALEOZOIC SEDIMENTS

Rock formations deposited during the Paleozoic Era are found throughout Region 7, and these deposits are predominantly marine limestones and shales. The deep-water marine limestones, shales and dolomite deposits are interrupted by shallow water shale and sandstone deposits of the Upper Cambrian to Lower Ordovician Systems, of the Upper Devonian System, and of the Middle Pennsylvanian System. Since the Paleozoic Era is represented throughout Region 7, the following discussions of the hydrogeology of these deposits is divided into three subdivisions: 1) Eastern Paleozoic rocks; 2) South central Paleozoic rocks; 3) Western Paleozoic rocks.

Eastern Paleozoic Rocks

In the eastern states, the pre-Mississippian rocks are commonly found at depths too great to be considered for economical ground-water supplies. Exceptions to this are local areas along the Cincinnati Arch and the "driftless area" of Wisconsin where older formations are exposed. Central Tennessee, at the southern end of the Cincinnati Arch, and the "driftless area" contain near surface rock formations of Ordovician age. The younger formations have been eroded away, resulting in exposure of the Ordovician limestone deposits (Newcome 1958).

The Paleozoic sedimentary rocks of the "driftless area" of Region 7 are composed primarily of massive shales of Late Ordovician age, a thick sequence of carbonates of Middle Ordovician age, and blanket sandstones of Early Ordovician and Cambrian ages. The Paleozoic rocks onlap the crystalline basement of the Canadian Shield in Wisconsin.

The thick shale sequence of Late Ordovician age may be regarded as an aquiclude, and it provides confinement for the major aquifers below it. The carbonates of Middle Ordovician age are major aquifers and may yield up to 200 gallons per minute, depending upon the degree of fracturing in the rock. The thick sandstone units of Early Ordovician and Cambrian age are the most reliable and highest producing aquifers (yields often in excess of 1,000 gallons per minute) in the Paleozoic sequence. Where both the Ordovician and 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 commonly grouped together and the combined series of sandstones are commonly referred to as the Cambro-Ordovician Aquifer (Emerich 1966).

In the Canadian Shield portion of the "driftless area", 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.

In Missouri, the Cambrian to Ordovician sandstones yield small volumes of water and the limestones of Devonian and Mississippian age are commonly used for their ground-water resource. The groundwater becomes increasingly saline with depth and is often saline at shallow depths in locations where the presence of a Pennsylvanian-aged shale

cover inhibits recharge (Miller 1971). Well yields are commonly low, ranging from 10 to 25 gallons per minute. In other areas such as Kentucky, the Mississippian-aged limestones are found at depths of approximately 1,000 feet (Davis, Plebuch and Whitman 1974). Sandstones and limestones of Pennsylvanian age yield most of the groundwater from bedrock aquifers in the Eastern and Western Coal Field Regions of Kentucky. In the Bluegrass Region of north central Kentucky, the Middle Ordovician limestones produce most groundwater to wells in the area. The Mississippian-aged limestones in south central Kentucky are the major bedrock aquifers (Whitesides 1971). The yields are highly variable owing to the distribution of the secondary porosity caused by solution cavities and fractures. Generally, the yields are low, ranging from 10 to 30 gallons per minute (Whitesides 1971).

The Pennsylvanian sandstone deposits of the Caseyville Formation, the Tradewater Formation, Breathitt Formation and Lee Formation are becoming increasingly popular owing to the good water quality and larger well yields obtained from wells deep in these formations (Wilson and Van Couvering 1965; Davis, Plebuch and Whitman 1974). Groundwater in the Pennsylvanian sandstones often occurs in the channel deposits in the eroded Mississippian-aged rocks. Channel deposits are not present throughout the eastern states and their location is difficult to determine prior to drilling. These aquifers are significant in that they represent a high yielding source of good quality water in an area which was once believed to contain only saline water below a depth of 200 feet (Wilson and Van Couvering 1965; Davis, Plebuch and Whitman 1974). The Pennsylvanian sandstone deposits of the eastern states are considered a major aquifer of Region 7 and their aquifer data

are presented in Table 7-2. A discussion of the hydrogeologic properties is provided in a subsequent section of this chapter.

South-Central Paleozoic Rocks

Paleozoic-aged rock formations are found throughout the western parts of Kansas, Oklahoma, and Texas. Owing to their near surface occurrence and moderate to small yields, Paleozoic-aged limestones and sandstone formations are the common aquifers in the eastern portions of these states. The deposits range in age from Cambrian to Permian.

In Oklahoma and Texas, the oldest formations have been brought near the surface by structural features such as the Llano uplift in central Texas and the Arbuckle uplift in Oklahoma. In Oklahoma, the Cambrian- to Ordovician-aged Arbuckle Group contains thick, fractured, and cavernous limestones and dolomites. The Simpson Group of the Middle Ordovician age contains many beds of fine-grained, loosely cemented sandstone with yields commonly in a range of 100 to 200 gallons per minute with a maximum yield near 400 gallons per minute. Owing to the secondary porosity and lack of specific data, these formations are not included in the list of major aquifers.

Texas has a very similar hydrogeologic framework. The fractured openings and solution cavities of the Paleozoic marine sediments yield moderate to large volumes of groundwater to wells and are accessible and exposed to recharge in areas of structural uplifting. The Llano uplift, a Pennsylvanian-aged structure, has resulted in the surface outcrop of the Cambrian-aged Riley Formation in central Texas. The Hickory Sandstone Member of this formation has well yields ranging from 100 gallons per minute to a maximum of 1,200 gallons per minute with an average of about 500 gallons per minute. Typical well depths

for this formation are 500 feet below land surface (Mason 1961). This formation is considered a major aquifer in Region 7 and specific aquifer data are presented in Table 7-2. The hydrogeologic properties are discussed further in a subsequent section of this chapter.

The upper Paleozoic-aged deposits include Pennsylvanian-and Permian-aged sandstones, shales and some limestone rock formations. Often, the Pennsylvanian-and Permian-aged rock formations are overlain by Quaternary alluvium, as is the Lansing Formation in northeastern Kansas. The Chanute Shale has interbedded sandstone aquifers, but the yields of these Pennsylvanian- and Permian-aged deposits are less than 50 gallons per minute (McNellis 1971). An exception to this is the Permian-aged Rush Springs Sandstone of west-central Oklahoma. This sandstone formation commonly has well yields greater than 50 gallons per minute and a maximum yield of 1,200 gallons per minute (Tanaka and Davis 1963). The Rush Springs Sandstone occurs at or near the surface and wells seldom exceed 150 feet in depth. Owing to its high well yield and a large areal extent in west-central Oklahoma (Tanaka and Davis 1963; Hart 1974), this formation is considered a major aquifer of Region 7 and is most likely representative of the upper Paleozoic-aged aquifers in the south central part of the region. Specific aquifer data are given in Table 7-2 and a more detailed discussion is presented in a subsequent section of this chapter.

Western Paleozoic Rocks

The Paleozoic-aged deposits common to the western part of Region 7 are found at great depths in the states of South Dakota, North Dakota, Montana, Wyoming, Colorado, and New Mexico. As stated in the Geologic Framework section, the rock formations are composed almost entirely

of limestone and dolomite with interbedded sandstone and shale. The pre-Mississippian rock formations are too deep for economical aquifers in this area of the region. The only exception to this is along a narrow band parallel to the eastern flank of the Rocky Mountains where these formations are exposed. However, their steep dip soon places these rock formations at depths well in excess of 1,000 feet below land surface (Miller 1976).

In many areas, the Mississippian-aged Madison, Pahasapa, and Englewood Limestones range from 1,800 to 3,600 feet below land surface (Whitcomb and Morris 1968). The Pennsylvanian- and Permian-aged Minnelusa Formation, Tensleep Sandstone and Amsden Formation are sometimes found above a 1,000 foot depth, but frequently average from 1,500 to 3,500 feet below land surface. The well yields from these formations are highly variable and range from 20 to more than 200 gallons per minute. The yields are often a function of the fracture porosity (secondary porosity) associated with these highly deformed formations. Owing to the limited near surface occurrence of the western Paleozoic rocks and the dominant secondary porosity (Konikow 1976), no major aquifers were selected from this group of rock formations.

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 major aquifers of Region 7. The Hydrogeologic Framework section of this chapter described the general occurrence of groundwater and discussed many water-yielding rock formations, regardless of their areal extent or yield characteristics. The following sections will discuss only those aquifers previously described as major aquifers.

Specific data pertaining to each major aquifer's quantitative properties are tabulated and listed according to porosity group in Table 7-2. The qualitative geologic characteristics of each hydrogeologic environment are generalized and also presented in Table 7-2. The specific reference for which quantitative data are 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 7 have been evaluated according to the guidelines established in the Introduction of this report. 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 at this time to be unsuitable for ATES are discussed below, together with the justification for their elimination from further consideration. The aquifers are discussed according to the hydrogeologic environments established in the Hydrogeologic Framework section of this chapter: 1) Cenozoic unconsolidated deposits; 2) Tertiary deposits; 3) Cretaceous marine sediments; 4) Lower Mesozoic sediments; 5) Paleozoic sediments. Figure 7-6 provides a listing of the major aquifers in Region 7 considered at this time to be unsuitable for ATES.

CENOZOIC UNCONSOLIDATED DEPOSITS

The major aquifers of the unconsolidated deposits are those associated with river alluvium and valley fill deposits. In general, such deposits have a high primary porosity owing to the unconsolidated and uncemented nature of the sand and gravel particles. The groundwater is most often under water table conditions, with a slight gradient towards the associated river, and in the direction of stream flow; this gradient may change somewhat in response to river stage.

Alluvial deposits associated with Quaternary and Recent stream channels are often the results of rapidly changing sedimentary depositional environments in response to glacial activity, floods, droughts,

AQUIFER	REASONS FOR UNSUITABLE RECOMMENDATIONS	COMMENTS
Cenozoic Unconsolidated Deposits - 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 the alluvial aquifer is suitable for A.T.E.S. at a particular location.
Tertiary Sediments - Wasatch Formation - Tesuque 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 aquifers are suitable for A.T.E.S. at a particular location.
Cretaceous Marine Sediments - Woodbine 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.
Lower Mesozoic Sediments - Santa Rosa 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. However, site-specific studies may delineate areas where the aquifer is unfractured and may be suitable for A.T.E.S. in these areas.
Paleozoic Sediments - Carbonate Rocks - Hickory Sandstone	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.
- Rush Springs Sandstone - Pennsylvanian Sandstone	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 7

and man-caused events. Owing to such environments, alluvial deposits often vary in composition and change frequently from permeable gravels to impermeable silts and clays. As a result of this rapid and frequent facies change, the hydrologic properties often vary significantly over short distances. Often, when a large areal extent of permeable alluvium is present, the aquifer has a coefficient of transmissibility exceeding 100,000 gallons per day per foot (Hurr and Moore 1972; Weist 1965-A). Excessive aquifer transmissibility is undesirable for ATES because it results in high pore velocities and low recovery efficiencies.

In many river valleys, aquifers exist in the less permeable sand and silt deposits of flood plain origin. Such deposits may have properties favorable for ATES. However, the distribution of favorable deposits would be on a more local than regional basis. The regional scope of this study dictates that the sub-regional aquifers be eliminated from further consideration. Therefore, the Cenozoic unconsolidated deposits are considered unsuitable for ATES. Site-specific studies, concentrating on the less permeable sand and gravel deposits, may delineate aquifers in this hydrogeologic environment which have ATES potential.

TERTIARY SEDIMENTS

In the Hydrogeologic Framework section of this chapter, three Tertiary-aged rock formations were delineated as major aquifers. Two of these aquifers, the Eocene-aged Wasatch Formation in northeastern Wyoming and the Miocene (?) - Pleistocene (?) aged Tesuque Formation of north central New Mexico, are considered unsuitable for ATES.

The water-yielding strata of the Wasatch Formation are the lenticular sandstone beds found in the two conglomeratic members, the Kingsbury Conglomerate and the overlying Moncrief Member. Although the yield of these two members is greater than 50 gallons per minute throughout their areal extent, their hydrologic properties may not be continuous throughout their extent. The Kingsbury Conglomerate Member was deposited upon the eroded surface of the underlying formation and may represent extensive alluvial fan deposits (Whitcomb, Cummings and McCullough 1966). The data reported for this aquifer are marginally acceptable for ATES, but there is a possibility of secondary porosity from coal and clinker beds (Hodson, Pearl and Druse 1973) and the potential for discontinuous and variable aquifer characteristics. Owing to these uncertainties, the Wasatch Formation is considered unsuitable for ATES. Site-specific studies may identify local areas with potential for small system ATES facilities within this formation.

The Tertiary-aged deposits in southern Colorado and New Mexico often contain large amounts of volcanic debris and interbedded lava flows. This type of sediment is characteristic of the post orogenic geologic environment that existed during the Miocene and Pliocene periods in the southwestern part of Region 7. A typical major aquifer in this environment is found in the Santa Fe Group of north central New Mexico. This group is a part of the Pajarito Plateau. The Tesuque Formation of the Santa Fe Group is a moderately cemented siltstone and sandstone with lenses of conglomerate, clay, and interbedded basalt. The underlying Puye Formation is a poorly consolidated conglomerate channel-fill deposit with conglomerate of volcanic debris

and arkosic sediments (Purtymun and Cooper 1969). These formations yield large volumes of water to wells penetrating great thicknesses of this material. Well yields of 1,400 gallons per minute each are reported for two wells with approximate depths of 2,300 feet below land surface (Purtymun and Cooper 1969). The qualitative aquifer characteristics are acceptable for ATEs use; the coefficient of transmissibility is approximately 15,000 gallons per day per foot and the well yield averages above 500 gallons per minute (Cushman 1965). Owing to the depositional environment, the water-yielding formations are not continuous throughout the extent of the Santa Fe Group. The aquifers are also interbedded with lava flows which interrupt the hydrogeologic continuity desirable in a thermal energy storage aquifer. Additionally, the main aquifer is 1,200 feet below land surface in some areas, and the shallowest lies 600 feet below land surface towards the east side of the Parjarito Plateau (Purtymun and Cooper 1969). Throughout much of the aquifer's areal extent it lies at depths greater than 1,500 feet, which may also be undesirable for ATEs facilities. This aquifer is considered undesirable because of its variable geologic composition and excessive depths.

CRETACEOUS MARINE SEDIMENTS

In previous sections of this chapter, the Cretaceous-aged marine sediments were characterized as thick sequences of relatively impermeable marine deposits of shales, limestones, and interbedded sandstones. The majority of Cretaceous-aged sediments are not considered major aquifers owing to their low well yields (less than 50 gallons per minute). The Cretaceous-aged sediments in Region 7 often contain a

basal sandstone deposited in a near shore (littoral) to continental environment and represent a major aquifer. Throughout the Cretaceous record, varying thicknesses of sandstones were deposited as the epeiric sea transgressed and regressed. In the course of a regional study such as this, only a few of the more common aquifers with readily available hydrogeologic data are discussed and evaluated. A more detailed, site-specific study of the various interbedded sandstones and shales may provide sufficient data to identify other aquifers with ATEs potential. For the purpose of this study, only three Cretaceous-aged major aquifers were identified; two sandstone deposits in the Lower Cretaceous System and one sandstone formation of the Upper Cretaceous System. The Upper Cretaceous shale and sandstone formation is considered unsuitable for ATEs and is discussed in this section.

The Woodbine Formation, as described by Leggat (1957), unconformably overlies the Washita Group of north central Texas and consists of ferruginous, fine-grained sandstone, clay, sandy clay, lignite, and gypsum. The formation consists of two members, the Dexter Member and the overlying Lewisville Member. Both members yield mineralized water typically high in iron; the Dexter Member generally has higher yields of better quality water. This formation is considered unsuitable for ATEs owing to the lenticular nature of the sandstone beds and the secondary porosity associated with the lignite beds (Leggat 1957; Baker 1960). The water-yielding strata are not continuous throughout the formation's extent. In south central Oklahoma, the formation yields very small volumes of water owing to the increase in the shale content and an increase in the cementation of the sandstone beds (Hart 1974).

LOWER MESOZOIC SEDIMENTS

The Lower Mesozoic sedimentary record is scarce throughout Region 7. Sediments deposited during the Triassic and Jurassic Periods are present in the southwestern part of the region and in a few localities in central Kansas. The geologic depositional environment was continental and, therefore, the Lower Mesozoic sediments are predominantly fine-grained, continental, red sandstone and shales with minor limestones. Well yields are generally much less than 50 gallons per minute and are seldom greater than 10 gallons per minute (Berkstresser and Mourant 1966). An exception to this is the sandstone formation of the Dockum Group and the San Rafael Group in western Texas and east central New Mexico. Sufficient data were not available for the Entrada Formation of the San Rafael Group so it has not been considered as a major aquifer of Region 7. Further research of the San Rafael Group may provide sufficient data to allow evaluation of the Entrada Formation. The Dockum Group contains the Santa Rosa Formation in east central New Mexico and western Texas. This formation is considered a major aquifer and is evaluated in the following paragraph.

The Lower Triassic Santa Rosa Formation is known to yield to wells from one to 50 gallons per minute and flows to springs at 150 gallons per minute in east central New Mexico (Berkstresser and Mourant 1966). In the southeast corner of New Mexico and west Texas, the Santa Rosa is an important aquifer yielding from 160 to 400 gallons per minute to wells commonly less than 600 feet below land surface. The coefficient of transmissibility ranges from 12,000 to 37,000 gallons per day per foot and averages 22,000 per day per foot (Garza, Sergio and Wesselman

1962). The depth, the areal extent, and hydrologic characteristics are acceptable for ATEs. However, it is likely that post Triassic crustal movements have fractured the rock formation and local high yields result from secondary porosity (Garza, Sergio and Wessleman 1962). Brown, Rogers and Baker (1965), report that the Santa Rosa is commonly a consolidated sandstone yielding small amounts of water. In some areas, the Santa Rosa Sandstone is fractured, greatly increasing the permeability of the formation and allowing moderate to large amounts of water to be drawn from the aquifer. This is most likely the reason for high yields in western Texas (Winkler County) near the southeast corner of New Mexico. In this area, the collapse of the underlying Paleozoic karst topography is known to cause extensive basins to develop with great vertical relief (Garza, Sergio and Wesselman 1962). Owing to the potential for secondary porosity, the Santa Rosa Formation is considered unsuitable for ATEs although site-specific studies may delineate areas of this formation with ATEs potential.

PALEOZOIC SEDIMENTS

The predominant type of aquifer in the Paleozoic sedimentary rocks of Region 7 is associated with fractures and solution cavities developed in the carbonate rock types (limestones and dolomites). As established in the aquifer evaluation guidelines of this report, aquifers associated with secondary porosities are considered undesirable for ATEs because of their somewhat random and unpredictable volumes of stored water. Therefore, the carbonate aquifers associated with the Mississippian, Devonian, Silurian, and Middle Ordovician Systems are eliminated from further consideration for ATEs.

There are many Pennsylvania-aged sandstones which yield the minimum requirement of 50 gallons per minute and could be suitable for ATES. Few data have been generated for these sandstones, and the available data is presented in Table 7-2. The Pennsylvanian sandstones are alluvial channel sandstones associated with continental deposition and, therefore, have a sub-regional or local 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 more accurately determine whether a Pennsylvanian-aged sandstone at a given locality is suitable for ATES. The other major Paleozoic-aged aquifers are associated with named formations and are discussed in the following paragraphs.

A specific major Paleozoic-aged aquifer is the Cambrian-aged Hickory Sandstone Member of the Riley Formation. This formation, found in central Texas, is typical of many Lower Paleozoic sandstone aquifers. Owing to the Llano Uplift of late Paleozoic time, the Hickory Sandstone was brought to the surface where it receives recharge and is within a reasonable depth for economic water-supply wells. The favorable properties of this aquifer are the coefficient of transmissibility, which ranges from 19,000 to 38,000 gallons per day per foot, and the well yield, which ranges from 100 to 1,200 gallons per minute and averages approximately 500 gallons per minute. The Hickory Sandstone Member has two characteristics which make it unsuitable for ATES. The first characteristic is the steep dip resulting in a depth of 2,300

feet below land surface in some of the northwestern areas (Mason 1961). Although the formation may have sufficient areal extent, the water-yielding strata are not always within an economical distance from land surface throughout the extent. The second undesirable property is the presence of secondary porosity owing to extensive faulting and fracturing during the late Paleozoic-aged uplift. The Hickory Sandstone Member is considered unsuitable for ATEs for the above reasons, but site-specific studies may determine local areas where some ATEs potential exists.

The Permian-aged Rush Springs Sandstone in west central Oklahoma is another specific Paleozoic-aged aquifer. These sandstones were deposited in the Anadarko syncline basin and are major aquifers throughout the western sandstone hills area of Oklahoma. The sandstone formations contain interbedded gypsum layers which, in some areas, have solution cavities as suggested from drillers' logs (Tanaka and Davis 1963). There is also the potential for additional secondary porosity owing to the structural movements of the Anadarko syncline. In some areas, the Rush Springs Formation has yields below 15 gallons per minute (Hart 1974). These undesirable characteristics led to the determination that the Rush Springs sandstone is unsuitable for ATEs. But site-specific studies would be required to accurately assess the formation's ATEs potential because of the uncertainty of secondary porosity occurrence and the potential for favorable ATEs conditions.

Aquifers associated with secondary porosities are considered undesirable for ATEs owing to their somewhat random and unpredictable volumes of stored water. Therefore, the carbonate aquifers and crystalline basement aquifers of the "driftless area" of Region 7 are eliminated from further ATEs consideration.

AQUIFERS SUITABLE FOR ATES

Data gathered on aquifers in Region 7 indicate that there are many aquifers throughout the region that may be suitable for ATES. The data provided in Table 7-2 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 aquifers which may be suitable for ATES is organized according to format established in the Hydrogeologic Framework section of this chapter. The aquifers considered at this time to be suitable for ATES are listed in Figure 7-7.

TERTIARY SEDIMENTS

The Arikaree Formation has potential for ATES development. Of early Miocene age, the Arikaree is an aquifer of large areal extent occurring throughout eastern Wyoming, parts of western South Dakota, Montana, and southwestern North Dakota. The formation is composed of very fine-grained, poorly bedded, loosely to moderately cemented sandstone and interbedded silt, limestone, and many concretionary layers (Crist 1977). The water-yielding strata found at a favorable depth seldom exceed 350 feet below land surface and commonly range about 120 feet below land surface. The coefficient of transmissivity is in the acceptable range, with an average near 30,000 gallons per day per foot and a maximum of 60,000 to 77,000 gallons per day per foot (Whitcomb 1965; Crist 1977). The lithology is favorable in that there is an absence of lenticular layers of high permeability. A basal conglomerate bed is

AQUIFER	TYPES OF A.T.E.S. STORAGE	COMMENTS
Tertiary Sediments — Arikaree Formation	Large system — low, chill storage	The shallow depth and lack of confinement may rule out the potential for high temperature storage.
Cretaceous Marine Sediments — Trinity Group — Dakota Sandstone	Small system — high, low storage	The yield data and low transmissivity values favor the development of a small system A.T.E.S. facility.
	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 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.
Paleozoic Sediments — Cambrian Sandstones — Cambro — Ordovician Sandstones	Large system — high, low, chill storage	The typical well yield, degree of confinement, and aquifer thickness indicates that these aquifers may be well suited for large system high temperature storage.

MAJOR AQUIFERS SUITABLE FOR A.T.E.S. IN REGION 7

FIGURE 7-7

present throughout the formation's extent. Groundwater occurs under unconfined conditions with a saturated thickness ranging from 100 feet to 700 feet (Crist 1977). The favorable post-orogenic depositional environment has resulted in very little fault displacement or secondary fracture porosity. The exceptions to this are the Rawhide Fault and Whalen Fault located in east central Wyoming where local transmissivity values indicate possible secondary porosity (Crist and Lowry 1972). The aquifer water temperature varies from 2.7° C to 10.5° C (Whitcomb 1965).

The quantitative hydrologic data are favorable and indicate the potential for a large system (greater than 500 gallons per minute) ATES facility for either low temperature or chill storage. The shallow depth and lack of confinement may rule out the potential for a high temperature storage facility. Site-specific studies are required for a more accurate determination of the Arikaree Formation's ATES potential.

CRETACEOUS MARINE SEDIMENTS

The Early Cretaceous-aged Trinity Group has potential for ATES development. The Trinity Group consists of the Paluxy Sand and the Travis Peak Formation and, in some areas, the Trinity Group is undifferentiated. The Trinity Group is composed of a basal conglomerate overlain by fine-grained, poorly consolidated, massive sandstone beds with interbedded lenticular clay layers. The clay layers are not continuous or extensive over large areas (Baker 1960). The Trinity Group is found throughout central and northern Texas and corresponds to the Antlers Sandstone Formation in south central Oklahoma. The Antlers Formation is an aquifer in southern Oklahoma which has geologic and

hydrologic characteristics which may be favorable for ATES. Although the aquifer associated with the Antler's Formation lacks sufficient specific data for consideration as a major aquifer for ATES development (Hart 1974).

The Paluxy Sandstone and Travis Peak Formation have a coefficient of transmissivity ranging from 2,600 gallons per day per foot to 12,500 gallons per day per foot, and averaging near 4,400 gallons per day per foot (Leggat 1957). The undifferentiated Trinity Group has a coefficient of transmissivity ranging from 300 to 4,700 gallons per day per foot and averages approximately 2,800 gallons per day per foot (Baker 1960). Maximum well yields are generally near 500 gallons per minute. Well depths are variable as the Trinity Group dips to the southeast from its outcrop area. Generally, wells are less than 1,000 feet deep except the deep, high-yielding city wells at Sherman, which penetrate the full thickness at a depth approaching 2,000 feet below land surface. The aquifer is confined by relatively impermeable shale and limestone and in some favorable topographic areas wells flow, but since the artesian head is declining, few wells now flow. The yield data and low transmissivity values favor the development of a small system (less than 500 gallons per minute) ATES facility. The depth and degree of confinement are acceptable for both high temperature storage and low temperature storage.

In general, sandstone deposits of Early Cretaceous age should be subjected to site-specific studies to determine their ATES potential, because in some areas structural features may have created secondary porosity and because specific aquifer data were not available for many formations with ATES potential. A few such formations are the Basal

Kootenai Formation in central Montana, known locally as the Third Cat Creek Sand (Feltis 1980; Zimmerman 1966-A). The Basal Kootenai Formation may possibly correlate to the Dakota Sandstone in Wyoming and South Dakota.

Throughout the western states of South Dakota, North Dakota, Kansas, Montana, and parts of Wyoming and Colorado, the Dakota Sandstone Formation is known as a major aquifer. It is predominantly a widespread, near-shore (littoral) 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 hydrogeologic data are difficult to find in the literature. Most of the information found on this aquifer in Region 7, presented in Table 7-2, was information about the aquifer in South Dakota (U.S.G.S. 1975; Schoon 1971). Table 7-2 provides what limited hydrogeologic data were available on the Dakota Formation. Without sufficient specific aquifer data, the aquifer's suitability for ATEs was determined by what is known about the general geologic conditions of the Dakota Sandstone Formation.

The geologic conditions (thickness, depth, lithology) vary markedly over the region. The confining conditions of the overlying shale formations result in flowing artesian conditions for many wells tapping the Dakota Sandstone. This is particularly true in south central South Dakota just west of the Missouri River where many wells are uncapped and flow continuously. 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 throughout the region, the hydrogeologic characteristics of the aquifer are also expected to vary significantly. Without adequate information at this time, it is premature to evaluate what type of ATES facility is suitable for the Dakota Sandstone Aquifer. It may be found after further study that areas of the aquifer are suitable for each of the different types of storage. However, temperature data show that the artesian Dakota Sandstone Aquifer commonly yields warm to hot water varying from 21° C to a maximum of 48° C. The generally high yields, ranging from 300 to 1,000 gallons per minute, would indicate that the Dakota Sandstone Aquifer is suitable for a large-system ATES facility. Site-specific data or further research of the available literature is required to accurately assess this aquifer's ATES potential.

PALEOZOIC SEDIMENTS

Throughout the "driftless area" of Region 7 the aquifers showing the most promise for ATES are the blanket sandstones of Ordovician and Cambrian age. The Lower Ordovician and Cambrian sandstones are commonly grouped together and referred to as the Cambro-Ordovician Aquifer.

Owing to the variable thickness, depth and hydrologic conditions over the extent of the Cambrian and Cambro-Ordovician Aquifers associated with the sandstone formations, site-specific information is needed prior to development of an ATES facility at a particular location. However, because of the typical well yield in excess of 1,000 gallons per minute, the degree of confinement, and aquifer thickness (greater than 100 feet), the Cambro-Ordovician Aquifer generally appears to be well suited for large system high temperature ATES facilities (Hogberg 1972; Emerich 1966).

REGION'S ATES POTENTIAL

Within Region 7, several aquifers show potential for ATES development. These aquifers indicate that other rock formations with a similar hydrogeologic environment may also have ATES potential. The aquifers and hydrogeologic environments showing the most promise for ATES development are as follows: 1) the Arikaree Formation deposited in the late Tertiary-aged (Miocene) post-orogenic environment on the east side of the middle and Northern Rocky Mountain Provinces; 2) the Trinity Group and Dakota Sandstone Formations, which represent the basal Cretaceous marine formations deposited in a near-shore transgressive sea environment; 3) the Cambro-Ordovician and Cambrian Aquifers located in the "driftless area". 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 7 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 which aquifers appear to have the greatest ATES potential.

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Region 8. Unglaciaded Appalachians

REGION 8 - UNGLACIATED APPALACHIANS

INTRODUCTION

Region 8 encompasses the area of the eastern United States that is the southern portion of the Appalachian Mountain system. The boundaries of the region are defined as the portion of the Appalachian Mountains south of the maximum extent of continental glaciation which occurred during the Pleistocene Epoch. The Piedmont province, the Blue Ridge - New England provinces, the Valley and Ridge province, and the Appalachian Plateaus province are the major physiographic divisions of the region (Fenneman et al. 1946). These physiographic provinces reflect the geologic and hydrologic framework of Region 8 (Figure 8-1).

The average annual precipitation varies from as much as 80 inches in an isolated area in the southern portion of the region to as little as 35 inches in an isolated area in the northern portion of the region. In general, the average annual precipitation ranges consistently from 40 to 50 inches over most of the region (Geraghty et al. 1973).

Groundwater is used for municipal, industrial, and rural domestic supplies. Determining how much groundwater is in storage in Region 8 and how much is available for development is difficult, because most of the groundwater in Region 8 is developed from fracture zones and solution cavities in the rocks. However, throughout most of the region, there is little evidence provided in the literature to suggest that aquifers are being overdrafted.

GEOLOGIC FRAMEWORK

As stated in the previous section of this chapter, the physiographic provinces reflect the geologic framework of Region 8. The general geology of each province is discussed below.

PIEDMONT PROVINCE

The Piedmont physiographic province is bounded on the east by the Fall Line, which is the intersection of the Piedmont province and the Coastal Plain province. The Piedmont province is bounded on the west by the Blue Ridge - New England physiographic provinces (Figure 8-1). and has a gently undulating surface. Throughout most of the region, the province is predominantly underlain by weathered crystalline metamorphic and igneous rocks (Sinnott and Cushing 1978). The Piedmont province may be separated into two physiographic subprovinces: 1) the Piedmont Upland; and 2) the Triassic Lowland (Sinnott and Cushing 1978; Parker et al. 1964).

Piedmont Upland

The Piedmont Upland is composed primarily of schists, gneisses, and granites of Precambrian age, with some highly metamorphosed sedimentary rocks (principally Ordovician carbonates), and some meta-volcanics. The ancient crystalline rocks of the Piedmont Upland have been highly folded and faulted (Parker et al. 1964), and in some areas the rocks are so highly metamorphosed that the original texture of the rocks is unrecognizable.

The crystalline rocks of the Piedmont province are blanketed by a veneer of weathered material called regolith. The regolith consists of

clay with lesser amounts of sand and large rock fragments. The fractured crystalline rocks are easily broken down in the humid temper climate, and the regolith may be up to 100 feet thick in some localities, particularly in the low-lying areas. However, the thickness of the regolith varies markedly from place to place and may be only a few feet thick, particularly on the upland surfaces (Floyd and Peace 1974).

Triassic Lowland

The Triassic Lowland of the Piedmont province is composed primarily of great thicknesses of sandstones and shales of Triassic age with some beds of siltstone and conglomerate (Sinnott and Cushing 1978; Parker et al. 1964; Floyd and Peace 1974). The Triassic sedimentary rocks were deposited by rivers and streams and have been relatively undeformed since the time of deposition (Dott and Batten 1971). Because of the fluvial origin of the sedimentary rocks, the beds are lenticular in most places and the lithology may differ considerably within short distances, both vertically and laterally (Floyd and Peace 1974). The Triassic Lowland of the Piedmont province has low ridges composed of diabase, basalt, and argillite which stand out because the rocks are more resistant to erosion than the softer sandstones and shales (Sinnott and Cushing 1978; Parker et al. 1964).

BLUE RIDGE - NEW ENGLAND PROVINCES

The southernmost extension of the New England province may be found in Region 8 and it is commonly referred to as the Reading Prong (Parker et al. 1964). The geology of the Reading Prong and the Blue Ridge province is so similar that the two provinces may be considered

equivalent (Sinnott and Cushing 1978; Parker et al. 1964). Both the Blue Ridge province and the New England province (Reading Prong) occur as very narrow belts in Region 8 (Figure 8-1). The Blue Ridge province and the New England province are characterized by igneous intrusive rocks and highly metamorphosed sedimentary rocks (crystalline rocks). The crystalline rocks of both the Blue Ridge province and the Reading Prong have been highly deformed. The Reading Prong is a topographic ridge and Blue Ridge province is a topographic mountainous region. In the topographically high areas, the crystalline rocks have a very thin veneer regolith. The regolith is substantially thicker in the stream valleys and lowlying areas (Trainer and Watkins 1975; Zurawski 1978; Cederstrom Boswell and Tarver 1979).

VALLEY AND RIDGE PROVINCE

The Valley and Ridge province, as the name implies, is a series of northeast-trending large ridges separated by valleys. The series of ridges and valleys actually represents a large system of folds, anticlines and synclines, and the province is commonly referred to as the "folded Appalachians" (Trainer and Watkins 1975). The bedrock of the Valley and Ridge province is composed of sandstones, shales, limestones, and dolomites of Paleozoic age (Sinnott and Cushing 1978; Cederstrom, Boswell and Tarver 1979; Zurawski 1978). These sedimentary rocks were deposited by seas that covered the region during Paleozoic time. Owing to the marine origin of the sedimentary rocks, the individual units are widespread, with the layers traceable for miles. The sedimentary layers have been folded and faulted.

APPALACHIAN PLATEAUS PROVINCE

The sedimentary rocks of the Appalachian Plateaus province are nearly flat-lying, in sharp contrast to the folded rocks of the Valley and Ridge province to the east. The sedimentary rocks are dominated by complex alternating sequences of sandstone, shale, limestone and coal. These sequences are from 20,000 to 30,000 feet thick (Sinnott and Cushing 1978). Marine environments were more prevalent in the deposition of the older and more deeply buried rocks (Ward and Wilmoth 1968). The lithologies of the older marine sedimentary layers, which are Early and Middle Paleozoic age, are widespread and may be traceable over miles. A continental environment developed later, during Pennsylvanian time, with fresh-water deltaic sedimentary rocks predominating at shallow depths. The sedimentary rocks of continental origin are characterized by rapid facies changes over short distances; therefore, lithologies cannot be traced either vertically or horizontally over distance.

HYDROGEOLOGIC FRAMEWORK

Because Region 8 is beyond the limit of continental glaciation, the unconsolidated material overlying the bedrock is relatively thin and not hydrogeologically significant. The only areas where the unconsolidated material is thick enough to be used as aquifers is in stream and river valleys. Therefore, the hydrogeologic framework of Region 8 is directly related to the bedrock geology of the region. As stated in the Introduction, the region may be divided into four distinct physiographic provinces. Likewise, the hydrogeologic framework can be separated

into four distinct regimes which correlate to the four different physiographic provinces. The following discussion outlines the general hydrogeology of each province.

PIEDMONT PROVINCE

The Piedmont province may be divided into two subprovinces: 1) the Piedmont Upland; and 2) the Triassic Lowland. The hydrogeologic framework of the Piedmont province may also be divided into two distinct subprovinces.

Piedmont Upland

There are two major factors that contribute to the well yields in the Piedmont Upland: 1) the degree of fracturing in the crystalline rocks; and 2) the thickness of the regolith (LeGrand 1967). Well yields in the Piedmont Upland are generally less than 75 gallons per minute, often less than 25 gallons per minute, but may be as high as 500 gallons per minute (Cederstrom, Boswell and Tarver 1979).

The aquifers of the Piedmont Upland are associated with the fractures developed in the crystalline rocks. The amount of water available to a well depends upon the number and size of fractures encountered while drilling at a particular location. The well yield at a particular location cannot be predicted prior to drilling. However, an understanding of the geologic structure of an area, that is the folding, faulting, and jointing, will enhance the probability of developing a successful well (Johnston 1960; Johnston 1962). Large ground-water supplies are usually developed along fault zones (Virginia Division of Water Resources 1969; Cederstrom Boswell and Tarver 1979).

Even though the regolith overlying the bedrock does not readily yield water to wells, it is hydrologically important as a source of ground-water storage and recharge to the underlying aquifers (Cederstrom, Boswell and Tarver 1976). Therefore, the greater the thickness of regolith at a given location, the greater the amount of ground-water in storage available to recharge the underlying aquifers.

Triassic Lowland

Aquifers of the Triassic Lowland area of the Piedmont province are associated with the sandstones and conglomerates of Triassic age. There are wells which produce high yields from these aquifers. The average well yield reported in southeastern Pennsylvania is 162 gallons per minute, with the highest reported yield approximately 440 gallons per minute (Cederstrom 1972). In the area of Virginia west of the District of Columbia, yields up to 600 gallons per minute have been reported from wells finished in the Triassic sandstones (Johnston 1960; Johnston 1962).

Because of the rapid facies changes associated with the Triassic sedimentary rocks, the sandstone and conglomerate units are not traceable over large distances. Many of the sandstone units are tight and have low permeabilities (Floyd and Peace 1974). In areas where the sandstones are well cemented, groundwater is developed from the fractures in the rock (Hall 1973; Parker et al. 1964; Johnston, 1960; Johnston 1962). The rapid facies changes of the Triassic sedimentary rocks coupled with the rapid changes in the character of the Triassic sandstones (i.e. degree of cementation) make it difficult to predict the depth and quantity of groundwater to be found at a given location (Hall 1973).

BLUE RIDGE-NEW ENGLAND PROVINCES

The geology of the Blue Ridge province and the New England province is roughly equivalent, as is the hydrogeologic framework of the two physiographic provinces.

The aquifers of the Blue Ridge and New England provinces are associated with the fracture systems developed in the crystalline rocks. In most places, the rock is massive and dense, and contains little water except where fractured and faulted. Throughout much of the upland slopes of these provinces the crystalline rocks are drained and the wells in these areas yield far less than 50 gallons per minute (Sinnott and Cushing 1978). The weathered rock material (regolith) is generally thin or absent on the upland slopes. In the valleys of the Blue Ridge and New England provinces, the regolith may be as much as 100 feet thick (Zurawski 1978) and the regolith is an important source of groundwater for recharging the underlying aquifers. Therefore, the amount of groundwater available in an area is directly related to the number and size of fractures in the rock, and to the thickness and permeability of the regolith (Cederstrom, Boswell and Tarver 1979, Trainer and Watkins 1975). Figure 8-2 is a sketch of idealized geologic and hydrologic conditions in the Blue Ridge province, which also apply to the New England province as well.

VALLEY AND RIDGE PROVINCE

The aquifers of the Valley and Ridge province are associated with the fractured sandstones and cavernous limestones and dolomites (Sinnott and Cushing 1978; Zurawski 1978). The sandstones are generally

NOT TO SCALE

SKETCH OF IDEALIZED GEOLOGIC AND HYDROLOGIC CONDITIONS IN THE BLUE RIDGE PROVINCE

(modified from Zurawski, 1978)

FIGURE 8-2

tight throughout the area and do not yield water to wells except where they are fractured (Sinnott and Cushing 1978; Zurawski 1978; Trainer and Watkins 1975). The wells in this province that rely on secondary porosity generally have a low recharge rate and often show great draw-downs (Cederstrom, Boswell and Tarver 1979). The fractures tighten with depth, so drilling below a depth of 300 feet is not recommended. In general, the poorest aquifers are the fractured sandstones, and the highest producing aquifers are the soluble carbonates (limestones and dolomites), with yields up to 1,100 gallons per minute from the Knox Dolomite (Zurawski 1978; Stewart et al. 1964). Figure 8-3 is a sketch of idealized geologic and hydrologic conditions in the Valley and Ridge province (Zurawski 1978).

APPALACHIAN PLATEAUS

The most reliable aquifers of the Appalachian Plateaus province are associated with the sandstones of Mississippian and Pennsylvanian age. The formations which contain these sandstones have been traced across the entire extent of the Appalachian Plateaus, from West Virginia to Alabama (Ward and Wilmoth 1968; Stewart et al. 1964). Owing to the continental origin of the sandstones, there are rapid facies changes within the formations which contain them and, therefore, the hydrologic conditions change rapidly from place to place (Ward and Wilmoth 1968; Stewart et al. 1974).

The hydrologic data for the sandstones shows a wide variability: yields range from less than 50 to 1,100 gallons per minute; transmissivity values range from 10,000 to 88,000 gallons per day per foot; and specific capacities range from 4.5 to 120 gallons per minute per foot of drawdown

NOT TO SCALE

SKETCH OF IDEALIZED GEOLOGIC AND HYDROLOGIC CONDITIONS IN THE VALLEY AND RIDGE PROVINCE

(modified from Zurawski, 1978)

FIGURE 8-3

(Wilmoth 1970). The yields of most wells drilled in the valleys commonly exceed those of the wells drilled on the hills, because the valleys are commonly formed along major fracture patterns which increase the permeability of the sandstones (Wilmoth 1970). The rocks older than Mississippian age are not important as aquifers but do produce oil, gas, and contain brine (Ward and Wilmoth 1968).

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 8. The Hydrogeologic Framework section of this chapter described the general occurrence of groundwater and discussed many water-yielding rock formations regardless of their areal extent or yield characteristics. Table 8-1 provides a listing of the major aquifers in the region. The following sections of this chapter will discuss only those aquifers previously described as major aquifers.

Specific data pertaining to each major aquifer's quantitative properties are tabulated and listed according to porosity group in Table 8-2. The qualitative geologic characteristics of each hydrogeologic environment are generalized and also presented in Table 8-2. 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.

MAJOR AQUIFERS UNSUITABLE FOR ATES

All of the major aquifers of Region 8 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 8-4 provides a listing of the major aquifers in Region 8 considered at this time to be unsuitable for ATES.

ALLUVIUM

As established in the Hydrogeologic Framework section of this chapter, the unconsolidated material in the unglaciated Appalachians is relatively thin. Even the alluvium along major streams is often too thin and areally restricted to offer promise for large ground-water supplies (Ward and Wilmoth 1968). Yields are generally less than 50 gallons per minute. However, there are isolated areas where the alluvium is capable of yields greater than 50 gallons per minute. 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. An alluvial aquifer may be confined in some areas and unconfined in others.

AQUIFER	REASONS FOR UNSUIT- ABLE RECOMMENDATION	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.
Igneous and Metamorphic (Crystalline) Rocks	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.
Carbonate Rocks	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 8

FIGURE 8-4

Site-specific studies may establish that, in some locations, alluvial sands and gravels 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.

IGNEOUS, METAMORPHIC AND CARBONATE ROCKS

Large ground-water supplies are developed throughout the Piedmont, Blue Ridge, New England, and Valley and Ridge provinces from fracture zones in the igneous and metamorphic rocks, and from solution cavities developed in the carbonate rocks. As established in the aquifer evaluation guidelines of this report, aquifers associated with secondary porosities are considered undesirable for ATES owing to the somewhat random and unpredictable volumes of stored water in these aquifers. Therefore, all of the igneous, metamorphic, and carbonate aquifers are eliminated from further consideration for ATES.

MAJOR AQUIFERS SUITABLE FOR ATES

Data gathered on aquifers in Region 8 indicate there are many aquifers throughout the region which may be suitable for ATES. The data provided in Table 8-2 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 8-5 contains a listing of the major aquifers in Region 8 which may be suitable for ATES.

TRIASSIC SANDSTONES

The Triassic sandstones located in the Triassic Lowland of the Piedmont province may have potential for ATES. As established in the Geologic Framework, the Triassic Sandstone(s) Aquifer is a series of continental sandstones, shales, and conglomerates, and the aquifer is capable of large yields (greater than 500 gallons per minute in some areas). The Hydrogeologic Framework section provided some hydrologic data for the Triassic Sandstone(s), but because of the rapid facies changes associated with the aquifer, 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. Without adequate information at this time, it is premature to evaluate what type of ATES facility is feasible for the Triassic Sandstone(s) 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).

Site-specific information for sandstone aquifers in the Valley and Ridge province may prove that these other sandstone aquifers are suitable for ATES at particular locations. Owing to the regional scope of this study and the sub-regional nature of these sandstone aquifers, their potential for ATES was not studied at this time.

PENNSYLVANIAN AND MISSISSIPPIAN SANDSTONES

The aquifers associated with the Pennsylvanian and Mississippian sandstones of the Appalachian Plateaus province may have ATES potential. The Pennsylvanian and Mississippian sandstone aquifers are a complex series of continental sandstones associated with shales, limestones and coals. They are capable of large yields (greater than 500 gallons per minute in some areas); however, geologic and hydrologic conditions vary markedly from place to place. The Hydrogeologic Framework section provided some hydrologic data for the Pennsylvanian and Mississippian sandstones, but because of the rapid facies changes associated with the aquifers, extensive site-specific information will have to be generated before making an adequate assessment of an aquifer's suitability for ATES. Without adequate information at this time, it is premature to evaluate what type of ATES facility is feasible for the Pennsylvanian and Mississippian sandstone aquifers. It may be found after further study that there are areas of the aquifers 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).

AQUIFER	TYPES OF A.T.E.S. STORAGE	COMMENTS
Triassic Sandstones	Small system — high, low, chill storage Large system — high, low, chill storage	Owing to the variable conditions within the aquifer, site-specific studies may prove that the sandstones are suitable for each of the different types of storage, depending upon the conditions at a particular location.
Pennsylvanian Sandstones Pottsville Group Allegheny Group Lower Conemaugh Group	Small system — high, low, chill storage Large system — high, low, chill storage	Owing to the variable conditions within the aquifer, site-specific studies may prove that the sandstones are suitable for each of the different types of storage, depending upon the conditions at a particular location.
Mississippi Sandstones Pocono Formation	Small system — high, low, chill storage Large system — high, low, chill storage	Owing to the variable conditions within the aquifer, site-specific studies may prove that the sandstones are suitable for each of the different types of storage, depending upon the conditions at a particular location.

MAJOR AQUIFERS SUITABLE FOR A.T.E.S. IN REGION 8

The Pennsylvanian and Mississippian sandstone aquifers with the best potential for ATEs are associated with the following formations: Pottsville Group; Allegheny Group; Lower Conemaugh Group; and the Pocono Formation. The hydrologic data for these aquifers are provided in Table 8-2.

REGION'S ATES POTENTIAL

Several aquifers in Region 8 show potential for thermal energy storage. The aquifers showing the most promise for ATES are: 1) the aquifers associated with the Triassic sandstones found in the Triassic Lowland of the Piedmont province; and 2) the aquifers associated with the Pennsylvanian and Mississippian sandstones of the Appalachian Plateaus province. The variable geologic and hydrologic conditions of all of these aquifers dictate that the sandstones may be suitable for each of the different types of storage, depending upon the conditions at a particular location. In all cases, site-specific information must be obtained before development of an ATES facility can be considered.

Owing to the regional scope of this study, only the regional aquifers of Region 8 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.

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Region 9. Glaciated Appalachians

REGION 9 - GLACIATED APPLALACHIANS

INTRODUCTION

Region 9 encompasses the area of northeastern Pennsylvania, portions of New York, northern Connecticut and Massachusetts exclusive of the Atlantic Coastal Plain, all of Vermont, New Hampshire and Maine (Figure 9-1). The region is defined as the eastern area of the United States which was periodically covered by ice masses during the Pleistocene Epoch. It is defined by the boundary marking the southern extent of maximum glaciation. The Appalachian Plateaus province, Valley and Ridge province, Adirondack province, and New England province are the major physiographic divisions of the region (Fenneman et al, 1946). These physiographic divisions reflect the geologic and hydrologic framework of Region 9.

The average annual precipitation ranges from 40 to 45 inches measured as rainfall and is rather consistent over the region. However, the proportion of precipitation that is snowfall varies markedly over the region. In general, the trend is from the Adirondack Mountains, which receive from 100 to more than 150 inches of snowfall per year, through the Appalachian mountainous areas, which receive 60 to 80 inches of snowfall per year, to the Coastal areas of the region that receive 40 to 60 inches of snowfall per year (Geraghty et al. 1973).

Groundwater is used for municipal, industrial, and rural domestic supplies. Data indicate that throughout Region 9 there is potential for further ground-water development without depleting ground-water resources.

GEOLOGIC FRAMEWORK

As stated in the previous section of this chapter, the physiographic provinces reflect the geologic framework of Region 9. The general geology of each province is discussed below.

APPALACHIAN PLATEAUS PROVINCE

The Appalachian Plateaus province is generally located in the southwestern portion of Region 9, bounded by the Valley and Ridge province on the east and by the Adirondack province on the north (Figure 9-1). The Appalachian Plateaus province is characterized by rocks that were undeformed during the Taconic (Appalachian) Orogeny and therefore are essentially flat-lying. The bedrock consists of alternating layers of sandstone, shale, limestone, and some seams of coal (Sinnott and Cushing 1978). These sedimentary rocks are predominantly of Pennsylvania and Mississippian age in Pennsylvania, and predominantly of Devonian age in New York. The sedimentary rocks of Pennsylvanian and Mississippian age are characterized by sequences of relatively thin layers of sandstone, shale, limestone, and coal. The sedimentary rocks of Devonian age have a characteristic sequence of thick, massive limestones and dolomites.

Glacial deposits blanket the Appalachian Plateaus area of Region 9. Till, deposited directly by glaciers as they advanced and retreated over the area, is generally found on the upland surfaces (Sinnott and Cushing 1978). The till is composed of an unsorted mixture of clay, silt, sand and gravel. In general, the matrix of the till is composed of fine-grained material with the coarser material suspended in the matrix. Outwash, deposited from the meltwaters of the continental glaciers, is generally found in the low-lying areas of Region 9 (Sinnott and Cushing

MAJOR PHYSIOGRAPHIC DIVISIONS OF
REGION 9 (after Fenneman and others, 1946)

FIGURE 9-1

1978). The outwash is composed of stratified sands and gravels that may extend for miles.

Ice-contact deposits at the margins of the ice masses are not as abundant in the Appalachian Plateaus province as they are in other provinces of the region. Ice-contact material will be discussed in the New England province section.

After the continental glaciers retreated, present-day streams and rivers filled their valleys with alluvium. The alluvium in a particular valley varies markedly in composition from place to place. In some areas, silt and clay associated with flood plain deposits are the dominant material; however, in other areas, sand and gravel associated with channel and point bar deposits are dominant.

ADIRONDACK PROVINCE

The Adirondack province is located primarily in northeastern New York and extends into the eastern portion of Vermont (Figure 9-1). The province is a nearly circular uplifted area composed of ancient granite, gneiss, and other crystalline rocks. The uplift is represented by mountains with many of the peaks exceeding 4,000 feet in elevation. The crystalline rock is surrounded by a sequence of tilted, metamorphosed, sedimentary rocks which are composed of sandstone, shale, limestone, and dolomite (Sinnott and Cushing 1978). Valleys that have developed on the surface of the uplift contain glacial outwash and alluvium. Till is found at the surface at higher elevations than the valley floors.

VALLEY AND RIDGE PROVINCE

The Valley and Ridge province lies to the east of the Appalachian

Plateaus province and the Adirondack province (Figure 9-1). Throughout Region 9, the Valley and Ridge province is only about 25 miles wide (Fenneman et al. 1946). Folding and faulting during the Taconic Orogeny created the valley and ridge topography which characterizes the province. The structural trend of the fold axes is generally northeastward in Pennsylvania and changes to a more northerly direction in New York. The bedrock of the Valley and Ridge province is composed of sandstones, limestones, dolomites, shales, and quartzites (Sinnott and Cushing 1978). The bedrock valleys are filled with glacial outwash and alluvium of Recent age.

NEW ENGLAND PROVINCE

The New England province lies directly to the east of the Valley and Ridge province in Region 9 (Figure 9-1). The bedrock exposed in the New England province is generally ancient crystalline basement, igneous and metamorphic rocks (Sinnott and Cushing 1978). There are two areas in the province where sedimentary rocks are exposed. Along the eastern border of New York and western borders of Connecticut and Massachusetts there is a thick sequence of metamorphosed carbonates (limestones and dolomites) which are Cambrian and Ordovician in age (Cederstrom 1972). These carbonates were apparently thrust into place from the west during the Taconic (Appalachian) Orogeny, and are highly fractured. Along the lower Connecticut River Valley, in Connecticut and Massachusetts, there is a thick sequence of continental sandstones and shales of Triassic age (Cederstrom 1972).

The valleys of the New England province are filled with glacial deposits and alluvium of Recent age. The glacial deposits are composed

of till, outwash, ice-contact material and eskers. Till and outwash were discussed in the Appalachian Plateaus province section of this chapter.

The ice-contact material is widespread in the New England province. It is composed primarily of sands and gravels deposited at the melting ice fronts during glaciation. In most other areas of the United States, the sand and gravel layers associated with ice-contact material are thin and discontinuous. However, in the New England province, the sand and gravel layers associated with ice-contact material may be up to 100 feet thick and may be traceable for several miles.

Eskers are also a dominant glacial feature found in the New England province. They are composed of channel sands and gravel deposited by streams located within the ice masses of Pleistocene time. Eskers are usually represented by sinuous sand and gravel ridges and are therefore not sand and gravel layers as are outwash and ice-contact material.

Along the coastal areas of Region 9, marine deposits of Pleistocene and Recent ages may be found. Dunes, beaches, and swamps are the sedimentary environments where marine deposits may be found. Well-sorted sands usually make up the dune and beach deposits and fine-grained material usually makes up the swamp deposits. In many areas of the coast, the marine deposits interfinger with the glacial deposits, causing rapid facies changes over short distances.

HYDROGEOLOGIC FRAMEWORK

The hydrogeologic framework of the region closely reflects the geologic framework of Region 9. Figure 9-2 shows the distribution and type of major aquifers in Region 9. A major aquifer is defined as an aquifer

LEGEND:

UNCONSOLIDATED AQUIFERS

Watercourse: alluvial valley traversed by streams from which recharge can be induced

Sand and gravel: in intermountain valleys; abandoned or buried alluvial valleys; alluvial terraces; sand dunes; Coastal Plains; glacial outwash and ice-contact deposits of glaciated regions.

CONSOLIDATED ROCK AQUIFERS

Sandstone: includes some unconsolidated sand.

Carbonate rock: limestone and dolomite.

DISTRIBUTION OF MAJOR AQUIFERS IN REGION 9
 (map, from U.S. Geological Survey, 1970 National Atlas
 of the United States),

which can typically sustain yields of at least 50 gallons per minute over the extent of the aquifer. There are regional aquifers which do not meet the minimum yield requirements (50 gallons per minute), so they are not represented in Figure 9-2. The following discussion provides the general hydrogeologic framework of Region 9. The discussion is separated into the hydrogeology of the bedrock versus that of the unconsolidated deposits.

BEDROCK HYDROGEOLOGIC FRAMEWORK

The hydrogeologic framework of the bedrock of Region 9 may be separated into three basic classifications: 1) the hydrogeology associated with igneous, metamorphic, and crystalline basement; 2) the hydrogeology associated with carbonates, primarily the Cambro-Ordovician carbonates; and 3) the hydrogeology associated with sandstones, primarily the Triassic sandstones.

Igneous, Metamorphic, and Crystalline Basement Hydrology

Igneous, metamorphic, and crystalline basement rocks are the predominant rocks exposed in the Adirondack province and New England province. Small to moderate ground-water supplies may be developed from these rocks where the rocks are fractured. Unfractured igneous, metamorphic, and crystalline basement rocks are tight and will not yield water. The amount of water available to a well depends upon the number and size of fractures encountered while drilling, but the well yield at a particular location cannot be predicted prior to drilling. The structural history of an area, i.e. the folding and faulting evidence in the rocks, provides the best information in predicting whether or not successful ground-water supplies may be developed.

Throughout most of the literature available on the hydrology of igneous, metamorphic, and crystalline basement rocks, all of the rocks are discussed as a single unit with respect to the occurrence of groundwater. There appear to be no significant differences in the water-bearing properties of these different rock types despite their distinctive physical properties (Bradley 1964). The groundwater in igneous, metamorphic and crystalline basement rocks is commonly under artesian conditions. The water usually will rise above the elevation of the aquifer, owing to the confinement provided by the impermeable bedrock walls of the fractures or joints. Confining pressure is also provided in locations where the bedrock is overlain by impermeable, unconsolidated deposits (Bradley 1964). Despite the small storage capacity associated with fracture porosity aquifers, the yields of wells finished in these aquifers are usually dependable owing to overlying saturated unconsolidated deposits (Bradley 1964). Because the yields of wells finished in igneous, metamorphic, and crystalline basement rocks varies dramatically from place to place (ranging from 1 to 100 gallons per minute), these aquifers are not considered major aquifers regionally and therefore are not represented in Figure 9-2.

Carbonate Rock Hydrogeology

Limestones and dolomites are present in all of the physiographic provinces of Region 9. Figure 9-2 illustrates the location of the major regional aquifers associated with carbonate (limestones and dolomites) rocks. Carbonate aquifers are also associated with the limestones of the Appalachian Plateaus province (Sinnott and Cushing 1978) and in the Arrostock Valley of Maine (Prescott Jr. 1966). These carbonate

aquifers are not represented on Figure 9-2 because they do not meet the minimum yield requirements of 50 gallons per minute.

As with the fracture porosity aquifers, ground-water supplies are developed from void spaces present in carbonate rocks. These void spaces have generally been developed through solution processes and are called solution cavities. The amount of water available to a well depends upon the number and size of the solution cavities encountered while drilling, but the well yield at a particular location cannot be predicted prior to drilling. In areas where the carbonate rocks have been folded and faulted, solution cavities are usually well developed.

There are two major carbonate rock sequences within Region 9 which are considered major regional aquifers: 1) the undeformed massive Paleozoic carbonates of central and northern New York; and 2) the highly deformed Cambro-Ordovician carbonates of the Taconic Sequence in southeastern New York, western Connecticut and western Massachusetts (Figure 9-2). Even though the Paleozoic carbonates of central and northern New York are not structurally fractured (folded or faulted), the development of solution cavities is sufficient so that municipal ground-water supplies can be developed from these rocks (Grossman and Yarger 1953). As stated in the Geologic Framework section, the carbonates of the Taconic Sequence are highly fractured. In some areas the degree of fracturing is so intense that the carbonates are considered to be "shattered" (Cederstrom 1972). Yields as high as 1,600 gallons per minute, with the average yield of 250 gallons per minute, are developed from the carbonates of the Taconic Sequence.

Sandstone Hydrogeology

Sandstones are present in all physiographic provinces of Region 9. The locations of the major sandstone aquifers are illustrated on Figure 9-2. Other sandstone aquifers are present throughout Region 9, but are not represented on Figure 9-2 because they do not meet the minimum yield requirement of 50 gallons per minute, or because the sandstone layers are not traceable for more than a few miles.

The water available for ground-water supplies from sandstone aquifers is commonly contained in and moves through the pore spaces of the sandstones. The amount of water available to a well depends upon the amount of cementation and how much interstitial silt and clay is present within a given sandstone. Sedimentological features, such as degree of rounding of the sand grains, also influences the amount of water available to a well. Well-sorted, rounded, uncemented sandstones are capable of sustaining large production wells. In general, none of the sandstone aquifers in Region 9 fall into that category. In most localities, the sandstones of Region 9 either are fine-grained with abundant silt and clay, or the sandstones have been recrystallized by metamorphic processes so that they are tight and yield little water to a well.

Along the Connecticut River Valley there are sandstones of Triassic age which, combined as a unit, are a regional aquifer and are an important source of water for rural homes, industries, and small municipalities. The Triassic Sandstone(s) are capable of moderately high yields in central Connecticut and high yields in central Massachusetts (Cederstrom 1972). The Triassic Sandstone(s), as this formation is commonly

referred to, are actually a sequence of red sandstones, shales, and conglomerates. These sediments are continental sediments, deposited by rivers and streams. Because of their continental depositional environment, there are rapid facies changes.

The water contained within the Triassic Sandstone(s) is contained in and moves through pore spaces, bedding planes, joints and faults (Cushman 1964). Apparently, in most locations the most important influence on the success of the well is the development of bedding planes and joints. A study of the Triassic Sandstone(s) in north-central Connecticut determined that the average porosity of the sandstones in that area is approximately 7 percent (Cushman 1964). The sandstones are highly cemented with calcium carbonate and yields in that area are generally less than 50 gallons per minute. The average specific capacity of the sandstone aquifers in that area was calculated as ranging from .01 to 10 gallons per minute per feet, with a median value of .1 gallons per minute per feet. Hydrologic data on the Triassic Sandstone(s) for other areas with more favorable conditions are not readily available in the literature. More site-specific information is needed to adequately evaluate the capabilities of the Triassic Sandstone(s) Aquifer.

UNCONSOLIDATED DEPOSITS HYDROGEOLOGIC FRAMEWORK

The hydrogeologic framework of the unconsolidated deposits of Region 9 may be separated into three major types of deposits: 1) the hydrogeology associated with the glacial deposits; 2) the hydrogeology associated with the marine deposits; and 3) the hydrogeology associated with the alluvial deposits.

Hydrogeologic Framework of Glacial Deposits

The glacial deposits in Region 9 are composed of till, outwash, ice-contact material, and eskers. Each of these four different types of glacial deposits have distinctive physical properties and different hydrologic characteristics. The following discussion outlines the hydrologic characteristics of each of the four types of glacial deposits.

Till - Owing to the general fine-grained matrix, till is commonly non water-yielding even when completely saturated. Very small groundwater supplies may be developed from till but usually only by use of dug wells. Till cannot be considered an aquifer in Region 9.

Outwash - Outwash deposits may be found throughout Region 9 and are, in general, the most reliable aquifers consistently producing high yields, as much as 500 gallons per minute (Cushman 1964). As stated in the Geologic Framework section of this chapter, outwash is composed of stratified sands and gravels which may extend for miles. The deposits are generally found at the surface in low-lying areas, such as river valleys, but may also be found on flat plains. In areas where the former course of a stream was altered during glaciation, a buried valley filled with outwash deposits is often left behind. Seismic data are needed to detect where a buried valley filled with outwash may be found.

Even though outwash deposits are generally widespread, the hydrologic conditions associated with these deposits vary over their geographic extent. The hydrologic characteristics of outwash deposits cannot be predicted without site-specific information. The productivity of an outwash aquifer depends upon factors such as thickness, areal extent, and ratio of sand and gravel to fine-grained material. Where outwash

is found in buried valleys it may be confined. However, outwash is commonly found at or near the surface and typically not under confined conditions.

Ice-Contact Deposits - The Geologic Framework section of this chapter discussed the general occurrence and physical properties of ice-contact deposits. With the exception of the New England province, ice-contact deposits are usually thin, localized sand and gravel deposits. Throughout the New England province, these deposits may be thick, extensive sequences of sand and gravel and capable of producing large ground-water yields of as much as 750 gallons per minute (Cushman 1964). The ground-water potential of the ice-contact deposits varies greatly from site to site; therefore, each aquifer requires individual study. Ice-contact deposits are generally exposed at the surface and therefore are unconfined. A comparison of hydrologic data for ice-contact deposits versus outwash, where the two different deposits occur at the same locality in the New England province, indicates that the ice-contact deposits are capable of producing more groundwater than the outwash (Sammel, Baker and Brackley 1966; Cushman 1964; Collins, Wiesnet and Fleck 1969; and Bradley 1964).

Eskers - Eskers are commonly major aquifers in the New England Province of Region 9. Many municipalities derive their water supplies from the sands and gravels found in eskers (Prescott, Jr. 1966; Hodges, Butterfield and Ashley 1976A). Yields from aquifers associated with eskers are reported to be as large as 1,250 gallons per minute (Prescott, Jr. 1966). Since eskers are distinct sinuous ridges on the land surface, the aquifers associated with eskers are unconfined. Well yields and hydrologic conditions vary from place to place, so site-specific data are needed to evaluate the capabilities of each aquifer.

Hydrologic Framework of Marine Deposits

For purposes of discussion, the marine deposits shall be separated into two different classifications according to sediment type: 1) the well-sorted sands; and 2) the fine-grained material. Neither the well-sorted sands or the fine-grained material are major aquifers in Region 9.

Well-sorted sands are associated with dune and beach deposits. In most areas dunes are above the water table (unsaturated) and therefore not capable of yielding water supplies. Beach deposits along the coast are saturated but are generally the ground-water supply for only small domestic supplies. Salt water intrusion has become a problem in some coastal areas, and it would be compounded with greater ground-water withdrawals.

The fine-grained marine deposits are often saturated, but are not water yielding and therefore not useful for developing ground-water supplies. However, in areas where the fine-grained marine deposits overlie glacial deposits, they may provide confining pressure for the glacial sands and gravels.

Hydrogeologic Framework of Alluvial Deposits

Throughout Region 9 are aquifers associated with the alluvial sands and gravels of Recent age. The aquifers are associated with present-day stream and river valleys. Perhaps the largest of the river valleys are the Hudson River and Connecticut River valleys. The alluvial aquifers 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. However, alluvial aquifers are capable of high sustained yields owing to rapid recharge, often from hydrologic connection with surface water.

MAJOR AQUIFERS

The previous sections of this chapter described the basic geologic framework and hydrogeologic framework for Region 9. In these sections the major aquifers of Region 9 were identified and generally described. Table 9-1 provides a listing of the major aquifers in the region. For the purpose of this study, a major aquifer is 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 9-1 do not meet the minimum yield requirements but are listed because of their widespread use.

Each of the major aquifers of Region 9 were evaluated for ATES potential according to the guidelines established in the Introduction. Data were gathered, stored, and tabulated by computer for those aquifers which appear to have some ATES potential. Table 9-2 is a computer listing of all data gathered for each aquifer in Region 9 that is believed to have some ATES potential.

AQUIFERS UNSUITABLE FOR ATES

All of the major aquifers of Region 9 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. The aquifers are discussed according to the format established in the Hydrogeologic Framework section of this chapter: 1) bedrock aquifers; and 2) unconsolidated aquifers. Figure 9-3 provides a listing of the major aquifers in Region 9 considered at this time to be unsuitable for ATES.

BEDROCK AQUIFERS

The predominant type of major bedrock aquifers in Region 9 are either those associated with fractures developed in igneous, metamorphic, and crystalline basement rocks, or those associated with solution cavities developed in limestones and dolomites. Ground-water supplies from secondary porosities can be developed from both types of aquifers. 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.

AQUIFERS	REASONS FOR UNSUITABLE RECOMMENDATIONS	COMMENTS
Igneous and Metamorphic (Crystalline) Rocks	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.
Carbonate Rocks	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.
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.
Local Outwash Sands and Gravels	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 the aquifer is suitable for A.T.E.S. at a particular location.

MAJOR AQUIFERS UNSUITABLE FOR A.T.E.S. IN REGION 9

FIGURE 9-3

UNCONSOLIDATED AQUIFERS

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 results in rapid facies changes. Because of these 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 locations and unconfined in other locations.

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.

Many sand and gravel aquifers associated with glacial outwash are also local and not regional in extent, particularly in the physiographic provinces other than the New England Province of Region 9. These thin, sub-regional outwash deposits are found in areas which were along the ice margin of the continental ice masses. These deposits reflect fluctuating 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.

AQUIFERS SUITABLE FOR ATES

Data gathered on aquifers in Region 9 indicate that there are many aquifers throughout the region which may be suitable for ATES. The data provided in Table 9-2 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 aquifers suitable for ATES is organized according to the format established in the Hydrogeologic Framework section of this chapter. Figure 9-4 provides a listing of the major aquifers in Region 9 considered at this time to be suitable for ATES.

BEDROCK AQUIFERS

The bedrock aquifer with potential for ATES is the Triassic Sandstone(s) Aquifer located in central Massachusetts and central Connecticut along the Connecticut River Valley (Figure 9-2). As established in the Geologic Framework section, the Triassic Sandstone(s) Aquifer is a series of continental sandstones, shales, and conglomerates. This aquifer is capable of large yields (greater than 500 gallons per minute in some areas). The Hydrogeologic Framework section of this chapter provides some hydrologic data for the Triassic Sandstone(s), but because of the rapid facies changes associated with the aquifer, 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. Without adequate information at this time, it is premature

AQUIFERS	TYPES OF A.T.E.S. STORAGE	COMMENTS
Triassic Sandstones	Small system – high, low, chill storage Large system – high, low, chill storage	Owing to the variable conditions within the aquifer, site-specific studies may prove that the sandstones are suitable for each of the different types of storage, depending upon the conditions at a particular location.
Widespread Sands and Gravels associated with Glacial Outwash, Eskers and Ice – Contact Deposits.	Small system – chill storage	Because these aquifers are usually unconfined, the depth to the zone of saturation at a given locality must be known before the aquifer's potential for A.T.E.S. can be evaluated.

MAJOR AQUIFERS SUITABLE FOR A.T.E.S. IN REGION 9

FIGURE 9-4

to evaluate what type of ATES facility is feasible for the Triassic Sandstone(s) 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).

Site-specific information for other sandstone aquifers in Region 9 may prove that these others are suitable for ATES at particular locations. Owing to the regional scope of this study and the sub-regional nature of these other sandstone aquifers, their potential for ATES was not studied at this time.

UNCONSOLIDATED AQUIFERS

Throughout Region 9 are aquifers associated with glacial sands and gravels which may be suitable for ATES. These aquifers, which are associated with outwash, eskers and ice-contact deposits, are commonly widespread and capable of sustaining large yields (up to 1,000 gallons per minute). Data gathered from site-specific studies in the New England province for each of these types of glacial deposits are provided in Table 9-2. Comparing the data for these glacial aquifers to the aquifer evaluation guidelines established in the Introduction indicates that the aquifers in these localities may be suitable for ATES. In most areas, the aquifers associated with outwash, ice-contact deposits and eskers are unconfined. Owing to the unconfined condition of these aquifers, they are probably only suitable for small system chill storage. The depth to the zone of saturation at a given locality must be known before the aquifer's potential for ATES can be evaluated. At present it is believed that a minimum thickness of 20 feet for unsaturated material

above the aquifer is needed for a small system chill ATES facility. Other hydrologic conditions of aquifers associated with glacial deposits vary over their extent, therefore site-specific information is needed before a complete evaluation of ATES potential can be made.

REGION'S ATES POTENTIAL

Several aquifers in Region 9 show potential for thermal energy storage. However, all of the aquifers indicating the most potential for ATES have highly variable hydrologic conditions over their extent. In all cases, site-specific information is needed before development of an ATES facility. The aquifers which regionally show the most promise for ATES are: 1) the Triassic Sandstone(s) Aquifer, which has insufficient data available in the literature to make an adequate assessment of ATES potential at this time; and 2) the aquifers associated with the sands and gravels of outwash, ice-contact deposits, and eskers, which are probably only suitable for small system chill storage because they are commonly unconfined.

Owing to the regional scope of this study, only the regional aquifers of Region 9 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 which aquifers appear to have the greatest potential for ATES.

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Region 10. Atlantic and Gulf Coastal Plain

REGION 10 - COASTAL PLAIN

INTRODUCTION

Region 10 encompasses the physiographic province known as the Coastal Plain, which is bounded by the southern and eastern coast of the United States and extends from Texas to Massachusetts. The intersection of the Coastal Plain and the continental highland areas is called the Fall Line, which represents the other boundary of the Coastal Plain. The Coastal Plain is nearly flat topographically, with a slightly undulating surface and no more than 250 feet of relief. In this report the Coastal Plain shall be divided into three major segments: the Gulf Coastal Plain; the Transition and Florida Coastal Plain; and the Atlantic Coastal Plain (Figure 10-1).

Data for the average annual precipitation of various areas within Region 10 were gathered from most of the references cited in the bibliography of this chapter. The average annual precipitation varies from less than 20 inches per year in southwest Texas, to 50 to 60 inches per year in the southern belt from Louisiana to North Carolina, to 40 to 50 inches per year from Virginia north to Massachusetts.

Ground-water usage also varies across the region. In the semi-arid areas of Region 10, primarily Texas, groundwater is depended upon for irrigation and livestock, in addition to municipal and domestic drinking water supplies. In Louisiana, Arkansas, and Alabama, tremendous volumes of groundwater are used for irrigation of rice, in addition to municipal and domestic drinking water supplies. Throughout

the remainder of Region 10, groundwater is used primarily as a source for municipal and domestic drinking water supplies, and is the major drinking water source for many of the large metropolitan areas.

GEOLOGIC FRAMEWORK

GENERAL FRAMEWORK

The general geologic framework of Region 10 is that of a basement rock complex, overlain by unconsolidated and semi-consolidated sedimentary deposits. The basement complex varies from Pre-Cretaceous sedimentary rocks in the Gulf Coastal Plain to crystalline igneous and metamorphic rocks of Pre-Cretaceous age in the Atlantic Coastal Plain. In general, the unconsolidated sedimentary deposits, which overlie the basement, are composed of sand, gravel, silt, clay, lignite, limestone, chalk, and marl. The clastic sedimentary formations of the Coastal Plain represent sandy, deltaic, continental deposition at the continental margin. In four states of Region 10 (i.e. the Transition and Florida segment of the Coastal Plain), limestones of Tertiary age are the dominant sedimentary rocks found overlying the basement complex (Cederstrom, Boswel, and Tarver 1979).

The surface of the basement complex of the Coastal Plain has a series of highs and intervening sags (Cederstrom, Boswell and Tarver 1979). Figure 10-2 shows the names and locations of these structural features. The features indicate that the basement has been tectonically active since Pre-Cretaceous time. The largest and most significant structural feature of the Coastal Plain is the Mississippi Embayment (Figure 10-3). The Mississippi Embayment is a structural, elongated trough, with an axis roughly paralleling the present course of the Mississippi River. The Cretaceous and older Tertiary sedimentary rocks dip toward the axis of the embayment. South of the Mississippi Embayment area, as delineated on Figure 10-3, the sedimentary rocks dip toward the Gulf of Mexico (Terry, Hosman and Bryant 1979).

STRUCTURAL FEATURES OF THE GULF COASTAL PLAIN

FIGURE 10-2

MISSISSIPPI EMBAYMENT

FIGURE 10-3

EXPLANATION

GENERALIZED GEOLOGIC CROSS SECTION OF COASTAL PLAIN AQUIFERS

FIGURE 10-4

Figure 10-4 is a generalized geologic cross section which illustrates the relationship between the Cretaceous age and younger sedimentary rocks and the basement complex. As depicted in the cross section, the sedimentary rock package is generally thin, a "feather edge", at the Fall Line and is a clastic wedge which thickens toward the coast, where there may be a maximum thickness of 8,000 feet to 10,000 feet. The formations are areally extensive.

The geologic cross section shows that sand and gravel layers, here depicted as aquifers, interfinger and intertongue with shale, marl, and lignite layers, here depicted as non-water-yielding deposits. Each sedimentary formation is generally overlapped by the next younger formation. In plan view the formations are exposed at the surface in a succession of older (inland) to younger (seaward) arcuate belts (Cederstrom, Boswell and Tarver 1979). Data from seismic studies and drilling information show that the sedimentary formations are rarely uniform laterally or downdip. In general the formations show changes of depositional environment which trend from near-shore, sandy, deltaic sediments at the inland edge of the formation, and grade downdip into deeper water, silty or limey marine deposits. Each of the formations generally thickens downdip. Data from seismic studies and drilling information also show that the shallow formations dip more gently, from 10 to 20 feet per mile, than the deeper formations, 30 to 50 feet per mile (Sinnott and Cushing 1978). Overlying the Cretaceous and Tertiary sedimentary rocks is a blanket of Quaternary-aged deposits.

Because there are so many stratigraphic units and associated nomenclature of the Coastal Plain, Figure 10-5 provides a general correlation of all of the stratigraphic units that make up the sedimentary

SYSTEM	SERIES	GULF COAST UNITS	FLORIDA UNITS	GEORGIA UNITS	SOUTH CAROLINA UNITS	NORTH CAROLINA UNITS	MARYLAND UNITS	NEW JERSEY UNITS	LONG ISLAND UNITS	
TERTIARY AND QUATERNARY	Holocene, Pleistocene, and Pliocene.	Post-Miocene Rock	Post-Miocene Rock	Post-Miocene Rock	Post-Miocene Rock	Post-Miocene Rock	Post-Miocene Rock	Post-Miocene Rock	Post-Miocene Rock	
	Miocene	Miocene Rock	Miocene Rock	Miocene Rock	Absent on Cape Fear arch.	Upper and middle Miocene rocks Lower Miocene rocks	Upper and middle Miocene rocks Lower Miocene rocks	Miocene and Eocene rocks un- differentiated.	Tertiary rocks undifferentiated.	
TERTIARY	Oligocene	Oligocene Rock	Oligocene Rock	Oligocene Rock	Absent on Cape Fear arch.	Rocks of uncertain age, possibly Oligocene in part.	No Oligocene known			Miocene and Eocene rocks un- differentiated.
	Eocene	Rocks of Jackson age	Ocala Limestone	Rocks of Jackson age	Rocks of Jackson age	Upper and middle Eocene rocks. Lower Eocene Rocks	Eocene rock undif- ferentiated.			
		Rocks of Claiborne age	Avon Park Limestone	Tallahatta and Lisbon Formations undiffer- entiated.	Middle and lower Eocene and Pale- ocene rocks undif- ferentiated.					
		Rocks of Wilcox age	Oldsmar Limestone	Rocks of Wilcox age						
Paleocene	Rocks of Midway age	Cedar Keys Limestone	Clayton Formation		Beaufort Formation	Paleocene Rocks	Paleocene ? Rocks			
CRETACEOUS	Upper	Gulf	Rocks of Navarro age	Rocks of Navarro age	Rocks of Navarro age	Rocks of Navarro age	Pedee Formation	Monmouth Formation	Monmouth Formation	Monmouth Formation
			Rocks of Taylor age	Rocks of Taylor age	Rocks of Taylor age	Rocks of Taylor age	Black Creek Formation	Matawan Formation	Magothy Formation and Matawan Group undiffer- entiated	Magothy Formation and Matawan Group undiffer- entiated.
			Rock of Austin age	Rocks of Austin age	Rocks of Austin age	Rocks of Austin age		Rocks of Austin age		
			Rocks of Woodbine and Eagle Ford age	Atkinson Formation	Rocks of Eagle Ford age Tuscaloosa Formation	Rocks of Eagle Ford age Tuscaloosa Formation	Rocks of Eagle Ford age Tuscaloosa Formation	Rocks of Eagle Ford age Tuscaloosa Formation	Raritan Formation	Raritan Formation
	Lower	Comanche	Rocks of Washita age	Rocks of Washita age	Lower Cretaceous	Lower Cretaceous	Rocks of Washita? age	Rocks of Washita? age	Rocks of Washita ? and Fredericksburg age undifferenti- ated.	Lower Cretaceous rocks absent.
			Rocks of Fredericksburg age	Rocks of Fredericksburg age			Rocks of Fredericksburg ? age	Rocks of Fredericksburg ? age		
			Rocks of Trinity age	Rocks of late Trini- ty age Sunni- land Limestone Rocks of early Trinity age.			Rocks of Fredericks- burg or Trinity age	Rocks of Fredericks- burg or Trinity age.		
									Rocks of Trinity?age	Rocks of Trinity?age
	P								Rocks of Trinity? age and older.	
		Lower Cretaceous (Neocomian) or Upper Jurassic	Lower Cretaceous (Neocomian) or Upper Jurassic	Lower Cretaceous (Neocomian) or Upper Jurassic	Lower Cretaceous (Neocomian) or Upper Jurassic	Lower Cretaceous (Neocomian) or Upper Jurassic	Mesozoic rocks of uncertain age, possibly Cretaceous	Mesozoic rocks of uncertain age, possibly Cretaceous		Lower Cretaceous (Neocomian) or Upper Jurassic

GENERAL CORRELATION OF STRATIGRAPHIC UNITS

(Adapted from Maher, 1971).

FIGURE 10-5

wedge of the Coastal Plain. Each of the units generally represents separate lithologic formations that are areally extensive. The geologic framework of the Coastal Plain is a simple model; that is, clastic and marine sediments deposited on the continental margin. However, the fluctuating depositional environment associated with deltas and a changing strand line provide for complex stratigraphy. The problem is compounded because formations are commonly given different names in different areas. This report will, when possible, group the formations together by time period (i.e., Cretaceous, Tertiary, and Quaternary) and by lithology rather than discuss each formation individually by stratigraphic name.

As stated in the Introduction, Region 10 can be separated on the basis of geology into three different segments: the Gulf Coastal Plain; the Transition and Florida Coastal Plain; and the Atlantic Coastal Plain. The following discussion provides a more specific geologic framework for each of the three different segments.

GULF COASTAL PLAIN

The dominant structural feature of the Gulf Coastal Plain is the Mississippi Embayment. The sediments of Pre-Cretaceous, Cretaceous and Tertiary age in the area of the embayment dip toward the axis of the embayment (Cushing et al. 1970). In the area of the Gulf Coastal Plain outside the embayment, the sediments of Cretaceous, Tertiary and Quaternary age dip toward the Gulf of Mexico. The sediments of Quaternary age are predominantly sands and gravels (outwash) deposited by meltwater streams from continental glaciers during the ice-

SYSTEM	SERIES	MISSISSIPPI	ALABAMA		FLORIDA			GEORGIA	
			Western	Southeastern	Panhandle	Peninsula			
Quaternary	Holocene and Pleistocene	Alluvium and terrace deposits	Alluvium and terrace deposits		Terrace deposits	Alluvium and terrace deposits its upper part of Biscayne aquifer. Dolomohatchee Marl		Alluvium and terrace deposits	
Tertiary	Pliocene	Citronelle Formation Graham Ferry Formation	Citronelle Formation	Absent	Citronelle Formation	Alachua Formation	Tamlami Formation	Charlton Formation	Duplin Marl
	Miocene	Pascagoula Formation Hattiesburg Formation Catahoula Sandstone	Undifferentiated		Unnamed course clastic Pensacola clay	Shoal River Formation Chipola Formation	Micoosukee Formation Hawthorn Formation	Hawthorn Formation	
						Tampa Limestone and equivalent		Tampa Formation	
		Paynes Hammock Sand Chickasawhay Limestone		Paynes Hammock Sand Chickasawhay Limestone	Absent	Chickasawhay Limestone		Flint River Formation	
	Oligocene	Vicksburg Group	Byram Formation Marianna Limestone Forest Hill Sand Red Bluff Clay	Byram Formation	Absent	Suwanee Limestone		Suwanee Limestone	
				Marianna Limestone		Byram Formation Marianna Limestone			
				Red Bluff Clay					
	Upper Eocene	Jackson Group	Yazoo Clay Moody's Branch Formation	Jackson Group	Yazoo Clay Ocala Limestone Moody's Branch Formation	Ocala Limestone		Ocala Limestone (lower part grades into Bornwell Formation up dip)	Cooper Marl (lower part)
	Middle Eocene	Clairborne Group	Cockfield Formation Cook Mountain Formation Sparta Sand Zilpha Clay Winona Sand Tallahassee Formation	Clairborne Group	Gasport Sand Lisbon Formation Tallahassee Formation	Avon Park Limestone Tallahassee Limestone Lake City Limestone		Clairborne Group	Gasport Sand Lisbon Formation (McBean Formation up dip) Tallahassee Formation
	Lower Eocene	Wilcox Group	Hatchatigbee Formation Tuscahoma Sand Nanolatia Formation	Wilcox Group	Hatchatigbee Formation Tuscahoma Sand Nanolatia Formation	Undifferentiated	Oldsmar Limestone	Wilcox Group	Hatchatigbee Formation Tuscahoma Sand Nanolatia Formation
	Paleocene	Midway Group	Naheola Formation Porters Creek Clay Clayton Formation	Naheola Formation	Absent	Undifferentiated	Cedar Falls Limestone		
				Porters Creek Clay Clayton Formation				Clayton Formation	
	Cretaceous	Upper Cretaceous	Selma Group	Prairie Bluff Chalk Ripley Formation Demopolis Chalk Coffee Sand Mooreville Chalk	Selma Group	Prairie Bluff Chalk Ripley Formation Demopolis Chalk Mooreville Chalk	Providence Sand Ripley Formation Demopolis P Chalk Mooreville P Chalk and Bufftown Formation	(Much as in southeastern Alabama, northeastward the post-Tuscaloosa Cretaceous Formations do not crop out and are difficult to differentiate in the subsurface.)	
			Eutaw Formation McShan Formation	Eutaw Formation McShan Formation	Eutaw Formation				
Tuscaloosa Group			Gorda Formation Coker Formation	Tuscaloosa Group	Gorda Formation Coker Formation	Undifferentiated	Tuscaloosa Formation		
Lower Cretaceous			Undifferentiated P		Undifferentiated P	Undifferentiated P			

GULF COASTAL PLAIN CORRELATION OF STRATIGRAPHIC UNITS

(Adapted from Cederstrom, Boswell, and Tarver, 1979)

FIGURE 10-6

age. The thickness of the Quaternary deposits ranges from 1,000 feet in southern Louisiana to over 3,500 feet in the Texas Gulf area (Harder 1960).

Figures 10-5 and 10-6 provide the stratigraphic nomenclature and correlation of the formations of the Gulf Coastal Plain. Throughout most of the Gulf Coastal Plain, areally extensive sand, gravel, clay, marl, limestone, chalk, and lignite layers are of Cretaceous and Tertiary age. In southern Louisiana, however, extensive blanket Quaternary sands and gravels are present. These strata also dip towards the Gulf of Mexico.

The Gulf Coastal Plain has been incised by present-day streams. Associated with the stream valleys are major sand and gravel terraces of Pleistocene age. Within the floodplain areas of the streams are alluvial deposits of Pleistocene and Recent age.

The alluvium of Pleistocene and Recent age consist of silt and clay flood plain deposits, and sands and gravels associated with stream channels and point bars. The major rivers in the Gulf Coastal Plain are the Mississippi River, the Red River and the Rio Grande River.

TRANSITION AND FLORIDA COASTAL PLAIN

Unlike the Gulf Coastal Plain and the Atlantic Coastal Plain, the sediments of middle Eocene to Oligocene age in the Transition and Florida Coastal Plain are primarily limestones, with only minor amounts of clastic sediments. These Tertiary limestones, however, interfinger with older and younger clastic rocks. The older clastic rocks are predominantly sandstones of Cretaceous age and are found at the surface along the Fall Line. The younger clastic rocks which directly overlie

the Tertiary limestones are generally silts and clays. Overlying the widespread silt and clay deposits are formations which are patchy and composed of sands and gravels (Cherry, Stewart and Mann 1970). There are no major rivers found in the Transition and Florida Coastal Plain, therefore Quaternary alluvium is not a major deposit. The stratigraphy and nomenclature of the formations found in the Transition and Florida Coastal Plain may be found on Figures 10-5 and 10-6.

ATLANTIC COASTAL PLAIN

The Atlantic Coastal Plain consists of the area between the crystalline rocks exposed in the Piedmont province of the Appalachian Mountains (Fall Line) and mean low tide (coastline). The Atlantic Coastal Plain may be divided into two major geologic provinces based upon the age and character of the unconsolidated sediments exposed at the surface. The two divisions are the Cretaceous- to Tertiary-aged deposits and the Pleistocene- to Recent-aged deposits.

Cretaceous and Tertiary Deposits

From South Carolina north to New Jersey most of the unconsolidated sediments are Cretaceous and Tertiary in age. These sediments are a seaward thickening wedge of sands, silts, clays and marls deposited by fluvial, deltaic, and marine processes on top of a Pre-Cretaceous basement complex (Virginia State Water Control Board 1974). In Maryland, Delaware, and New Jersey the Cretaceous- and Tertiary-aged deposits are blanketed by a veneer of deposits of Pleistocene and Recent age (Figure 10-4).

These Cretaceous and Tertiary sediments are exposed in arcuate bands roughly parallel to the present Atlantic Coastline. Upper Cretaceous sediments crop out almost continuously along the Fall Line. The sediments then become successively younger from the Fall Line to the coastline. Therefore, Tertiary sediments are exposed in broad patterns throughout most of the area of the Atlantic Coastal Plain (South Carolina to New Jersey) except in the area of the Cape Fear Arch where the Tertiary sediments are masked by a veneer of alluvial deposits. The Cretaceous and Tertiary sediments at the Fall Line are continental clastics, but these grade into clastics interspersed with some thin lignitic layers and marl beds in a seaward trend. The Cretaceous and Tertiary sediments at the coastline are marine in character. The thickness of the Cretaceous and Tertiary sediments increases to more than 10,000 feet at the coastline (Maher 1971).

Pleistocene and Recent Deposits

From New York (Long Island) north to Massachusetts the unconsolidated sediments are Pleistocene in age. These sediments are primarily blanket sands and gravels (outwash) deposited by meltwater streams during continental glaciation. In between the layers of outwash, marine silts and clays are commonly found. Overlying the Pleistocene deposits is a veneer of fluvial, fluviomarine and marine deposits of Recent age (McClymonds and Franke 1972; Mazzaferro 1973; Gonthier, Johnston and Malmberg 1978).

The topographic features from Long Island to Massachusetts are directly related to the glacial, fluvial, and marine events of Pleistocene and Recent age. Some of the prominent topographic features related to

these events are moraines, eskers, outwash plains, eroded headlands, valleys, and barrier beaches (McClymonds and Franke 1972; Mazzaferro 1973; and Gonthier, Johnston and Malmberg 1978). The types of sediments associated with the topographic features are sand and gravel, and silt and clay. There are rapid facies changes over short distances in the sediment type found exposed at the surface. With depth, however, areally extensive layers of sand and gravel with intervening fine-grained material are commonly found. This pattern is particularly evident on Long Island.

Figures 10-5 and 10-7 provide the stratigraphic nomenclature and correlation of the principal formations of the Atlantic Coastal Plain. The correlation of stratigraphic units generally stops at Long Island because north of Long Island the sediments of Pleistocene and Recent age may not be traced over distance and hence are not correlative.

SYSTEM	SERIES	STRATIGRAPHIC UNITS				INFORMAL UNITS USED IN THIS REPORT	AQUIFER NAMES USED IN THIS REPORT		
		Virginia	Maryland	Delaware	New Jersey				
Quaternary	Holocene	-----		-----		Quaternary sediments	Quaternary aquifer		
	Pleistocene	Columbia Group undivided		Columbia Group undivided					
Tertiary	Pliocene (P)	-----		Brandywine Formation		Cohansey Sand	Miocene sediments		
	Miocene	Chesapeake Group	Yorktown Formation	Chesapeake Group	Yorktown Formation			Chesapeake Group undivided	Kirkwood Formation
			St. Marys Formation		St. Marys Formation				
			Choptank Formation		Choptank Formation				
			Calvert Formation		Calvert Formation				
			Oligocene						
	Eocene	Chickahominy Formation	Piney Point Formation	Piney Point Formation	Piney Point Formation	Eocene and Paleocene sediments	Piney Point aquifer		
		Nanjemoy Formation	Nanjemoy Formation	Nanjemoy Formation	Shark River Formation Manasquan Formation				
	Paleocene	Aquia Formation	Aquia Formation	Rancocas Group	Vincentown Formation	Vincentown Formation	Aquia and Rancocas aquifer		
			Brightseat Formation		Hornerstown Sand	Hornerstown Sand			
Cretaceous	Upper Cretaceous	Mattaponi Formation	Monmouth Formation	Matawan Formation	Magothy Formation Raritan Formation	Potomac Formation	Tinton Sand	Marine Cretaceous sediments	
							Red Bank Sand		
							Navesink Formation		
							Mount Laurel Sand		
	Lower Cretaceous	Potomac Group	Patapsco Formation Patuxent Formation	Potomac Group	Patapsco Formation Arundel Formation Patuxent Formation	Potomac Formation	Raritan Formation and Potomac Group undifferentiated	Nonmarine Cretaceous sediments	Nonmarine Cretaceous aquifer
							Merchantville Formation		

EXPLANATION

No name assigned

Section not present

CORRELATION OF THE ATLANTIC COASTAL PLAIN STRATIGRAPHIC UNITS

(Adapted from Cushing, et. al., 1973)

FIGURE 10-7

HYDROGEOLOGIC FRAMEWORK

The hydrogeology of Region 10 is directly related to its geology, and in general reflects the model outlined in the geologic cross section provided in Figure 10-4. The aquifers are associated with sand and gravel layers and major limestone units found in the Gulf and Atlantic Coastal Plain. Limestones are the major aquifers and the sand and gravel layers are minor aquifers in the Transition and Florida Coastal Plain. The water quality becomes saline downdip in each of the aquifers. However, in areas away from the coast, potable water can usually be found at depths up to 2,000 feet.

The hydrogeologic framework of Region 10 can be separated into the three segments outlined in the Geologic Framework section: 1) Gulf Coastal Plain; 2) Transition and Florida Coastal Plain; and 3) Atlantic Coastal Plain.

GULF COASTAL PLAIN

The hydrogeologic conditions of aquifers found in the Gulf Coastal Plain not only vary from aquifer to aquifer, but conditions also vary within each aquifer from place to place. The variability of the hydrogeologic conditions may be attributed to the facies changes (i.e. continental to marine type sediments) which occur within each formation, the change in depth, and to the change in confining conditions owing to facies changes within the overlying and underlying formations. Therefore, the discussion of the hydrogeologic framework of the Gulf Coastal Plain will be general and consist of two principal groups: 1) aquifers associated with sediments of Pre-Cretaceous, Cretaceous and Tertiary

age; and 2) aquifers associated with sediments of Pleistocene and Recent age.

Pre-Cretaceous-, Cretaceous- and Tertiary-Aged Aquifers

The general hydrogeology associated with sediments of Pre-Cretaceous, Cretaceous and Tertiary age is essentially the same. The major aquifers of Pre-Cretaceous, Cretaceous and Tertiary age in the Gulf Coastal Plain are associated primarily with sand and gravel formations, and some limestone and chalk formations. The aquifers are recharged where the formations are exposed at the surface and ground-water movement is generally downdip to points of discharge through vertical leakage (Boswell et al. 1965; and Hosman et al. 1968). All of the aquifers are confined in places other than their outcrop areas (Terry, Hosman and Bryant 1979). In most areas where more than one aquifer is present, wells are constructed open to all of the aquifers present; therefore, the hydrogeologic characteristics represent all of the aquifers encountered (Newcome 1967).

As delineated in the Geologic Framework section of this chapter, older sediments are exposed inland, that is at the Fall Line and on the periphery of the Mississippi Embayment, and younger sediments are exposed at the coastline. Figure 10-4 provides a general geologic cross section and hydrologic cross section for Pre-Cretaceous, Cretaceous and Tertiary aquifers found in the Gulf Coastal Plain. There is insufficient data to outline the occurrence of fresh versus saline water in the Gulf Coastal Plain; therefore, test drilling and water sampling is required at each location.

Well yields of the Pre-Cretaceous, Cretaceous, and Tertiary aquifers vary greatly across the Gulf Coastal Plain. The yield within a

given aquifer varies according to the amount of coarse-grained versus fine-grained material in the clastic aquifers, the number of fractures and solution cavities in the carbonate aquifers, and other factors such as hydraulic connection to overlying and underlying aquifers. The well yield at a given location cannot be predicted prior to drilling. Yields from Pre-Cretaceous aquifers are generally small (Boswell et al. 1965). Yields from Cretaceous and Tertiary aquifers in many areas of the Gulf Coastal Plain may be several thousand gallons per minute (Boswell et al. 1965; and Hosman et al. 1968).

Pleistocene- and Recent-Aged Aquifers

There are two major types of aquifers of Pleistocene and Recent age found in the Gulf Coastal Plain: 1) blanket sand and gravel layers associated with outwash deposits of Pleistocene age; and 2) alluvial sands and gravels of Pleistocene and Recent age. The two different types of deposits have different morphologies and therefore different hydrologic characteristics.

The sand and gravel aquifers associated with outwash deposits are generally areally extensive and of uniform thickness. In places where these outwash aquifers are exposed in river terraces, they are usually above the water table and therefore capable of yielding only small supplies (Harder 1960). In locations where the outwash deposits are buried, they are commonly saturated and confined by overlying and underlying marine and lacustrine deposits and capable of sustaining large yields, up to several thousand gallons per minute (Harder 1960; Meyer and Turcan 1955).

In southern Louisiana and southern Texas the Pleistocene outwash aquifers have a hydrogeologic framework very similar to that of the

Pre-Cretaceous, Cretaceous, and Tertiary aquifers of the Gulf Coastal Plain. The aquifers are recharged in the outcrop areas and groundwater movement is downdip toward the Gulf.

The alluvial aquifers of Pleistocene and Recent age are found within present-day river and stream valleys and are hydrogeologically complex. The sands and gravels of these aquifers are 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. However, alluvial aquifers are capable of sustaining high yields owing to rapid recharge and are often in hydraulic connection with surface water. Well yield is greater than 500 gallons per minute and may be as great as 5,000 gallons per minute over 90 percent of the Mississippi River alluvial plain (Boswell, Cushing and Hosman 1968).

TRANSITION AND FLORIDA COASTAL PLAIN

The geologic framework of the Transition and Florida Coastal Plain is different from the Gulf and Atlantic Coastal Plain and therefore, the hydrogeologic framework of these plains is also different. The major aquifers in this portion of the Coastal Plain are associated with a thick sequence of limestones that range from middle Eocene to early Miocene in age. In Florida these limestone aquifers are referred to as the Florida Aquifer and the Biscayne Aquifer (Cherry, Stewart and Mann 1970; and Healey 1972). In Alabama, Georgia and South Carolina these aquifers are grouped together and commonly referred to as the Principal Artesian Aquifer (Counts and Donsky 1963; and Wait and Gregg 1973). Most of the limestone aquifers are part of an aquifer system because

they are hydrologically connected. Throughout the extent of the Tertiary limestone aquifers they are generally confined by Miocene silts and clays commonly referred to as the Hawthorne Formation (Leve 1961; and Counts and Donsky 1963). The Tertiary limestone aquifers provide tremendous yields, up to 4,200 gallons per minute, and are the major source of drinking water for the metropolitan areas of the region. Salt water encroachment is a problem in the Tertiary limestone aquifers in areas near the coast.

The sands and gravels occurring above and below the Tertiary limestone aquifers are generally used for only small ground-water supplies. At the Fall Line, however, the Cretaceous sand called the Tuscaloosa Formation is a major source of groundwater. The Tuscaloosa Sand Aquifer is capable of sustaining yields in excess of 1,000 gallons per minute, has a transmissivity value of 200,000 gallons per day per foot, and an average thickness of 600 feet (Siple 1967).

The sands and gravels of Quaternary age are generally not extensive, and many of them, such as river terraces and dunes, are above the zone of saturation. The aquifers associated with the Quaternary sediments are generally capable of providing water for only domestic usage.

ATLANTIC COASTAL PLAIN

There are two major different geologic provinces of the Atlantic Coastal Plain: 1) from South Carolina to New York (Long Island) sediments of Cretaceous and Tertiary age dominate; and 2) from New York (Long Island) to Massachusetts sediments of Pleistocene and Recent age

dominate. The hydrogeologic framework also differs from one province to the other.

Cretaceous and Tertiary Sediments

The hydrogeologic framework of the sediments of Cretaceous and Tertiary age found from South Carolina to New York (Long Island) is essentially the same as the hydrogeologic framework of the Gulf Coastal Plain (Maher 1971). Figure 10-4 provides a general hydrogeologic cross section for this portion of the Coastal Plain. The section of this chapter entitled "Pre-Cretaceous-, Cretaceous-, and Tertiary-Aged Aquifers" contains a detailed discussion of the hydrologic framework of the Gulf Coastal Plain, but it also applies to the portion of the Atlantic Coastal Plain from South Carolina to New York (Long Island).

Pleistocene and Recent Sediments

The hydrogeologic framework of the sediments of Pleistocene and Recent age of this portion of Region 10 from New York (Long Island) to Massachusetts may be separated into three major types of deposits: 1) the hydrogeology associated with glacial deposits; 2) the hydrogeology associated with marine deposits; and 3) the hydrogeology associated with alluvial deposits.

Glacial Deposits

The glacial deposits in this area of Region 10 are composed of till, outwash, and those deposits associated with eskers. Each of these three different types of glacial deposits have distinctive physical properties and differing hydrogeologic characteristics. The following discussion outlines the hydrogeologic characteristics of each of the three types of glacial deposits.

Till - Because of the general fine-grained matrix, till is commonly non water-yielding even when completely saturated. Very small ground-water supplies may be developed from till but usually only by use of dug wells. Till cannot be considered a viable aquifer throughout Region 10.

Outwash - Outwash deposits may be found throughout this portion of Region 10 and are, in general, the most reliable aquifers. They consistently produce high yields, as much as 2,000 gallons per minute (McClymonds and Franke 1972; Mazzaferro 1973; and Gonthier, Johnston and Malmberg 1978). As stated in the Geologic Framework section of this chapter, outwash is composed of stratified sands and gravels that may extend for miles. The deposits are generally found at the surface in low-lying areas, such as river valleys, but may also be found on flat plains. Long Island is underlain by several widespread outwash layers. In areas where the former course of a stream was altered during glaciation, a buried valley is left behind. These buried valleys are often filled with outwash deposits. Seismic data are needed to detect where a buried valley filled with outwash may be found.

Even though outwash deposits are generally widespread, the hydrogeologic conditions associated with these deposits vary over their geographic extent. The hydrogeologic characteristics of outwash deposits cannot be predicted without site-specific information. The productivity of an outwash aquifer depends upon factors such as thickness, extent, and ratio of sand and gravel to fine-grained material. In locations where outwash is found in buried valleys or associated with marine silts and clays, it may be confined.

Eskers - Eskers found in the northern portion of the Atlantic Coastal Plain may be major aquifers. Eskers are topographically distinct, sinuous ridges on the land surface composed of sand and gravel; therefore, the aquifers associated with eskers are unconfined. Well yields and hydrogeologic conditions vary from place to place so that site-specific data are needed to evaluate the capabilities of each aquifer.

Marine Deposits

For purposes of discussion, the marine deposits are separated into two different classifications according to sediment type: 1) the well-sorted sands; and 2) the fine-grained material. Neither the well-sorted sands nor the fine-grained material are major aquifers in Region 10.

Well-sorted sands are associated with dune and beach deposits. In most areas dunes are above the water table (unsaturated) and therefore are not capable of yielding water supplies. Beach deposits along the coast are saturated but are generally used for only small domestic supplies. Salt-water intrusion has become a problem in some coastal areas, and it could be compounded by greater ground-water withdrawals.

The fine-grained marine deposits are often saturated, but are not water yielding and therefore not useful for developing ground-water supplies. However, in areas such as Long Island, where the fine-grained marine deposits overlie glacial deposits, they may provide confining pressure for the glacial sands and gravels.

Alluvial Deposits

Throughout Region 10 aquifers are associated with the alluvial sands and gravels of Recent age. The aquifers are associated with present-day stream and river valleys, with perhaps the largest of the river valleys being the Hudson River and Connecticut River valleys. The alluvial aquifers are hydrogeologically 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. However, alluvial aquifers are capable of high sustained yields owing to rapid recharge, often from hydraulic connection with surface water.

MAJOR AQUIFERS

The previous sections of this chapter described the basic geologic framework and hydrogeologic framework for Region 10. In those sections the major aquifers of Region 10 were identified according to geologic age (i.e. Cretaceous, Tertiary, and Quaternary) and generally described. Table 10-1 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 tht can sustain typical well yields of at least 50 gallons per minute throughout its extent.

Each of the major aquifers of Region 10 was evaluated for ATES potential according to the guidelines established in the Introduction. Data were gathered, stored, and tabulated by computer for those aquifers appearing to have some ATES potential. Table 10-2 is a computer listing of all data gathered for each aquifer in Region 10 that is believed to have some ATES potential.

AQUIFERS UNSUITABLE FOR ATES

All of the major aquifers of Region 10 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 10-8 provides a listing of the major aquifers in Region 10 considered at this time to be unsuitable for ATES.

LIMESTONE AQUIFERS

Throughout Region 10, and particularly in the Transition and Florida portion of the Coastal Plain, major aquifers are associated with limestone formations. Ground-water supplies are developed from fractures and solution cavities developed in the limestones. 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 limestone aquifers are eliminated from further consideration for ATES. Likewise, all other aquifers, such as the Brunswick Shale, which develop ground-water supplies from secondary porosities, may also be eliminated from further consideration. Site-specific studies may determine that there are locations where these aquifers are suitable for ATES.

AQUIFER	REASONS FOR UNSUITABLE RECOMMENDATIONS	COMMENTS
Limestone Aquifers	Fracture Porosities	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.
Brunswick Shale and other Aquifers with secondary porosities.	Fracture Porosities	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.
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.

MAJOR AQUIFERS UNSUITABLE FOR A.T.E.S. IN REGION 10

FIGURE 10-8

ALLUVIAL AQUIFERS

As established in the Hydrogeologic Framework section of this chapter, the sand and gravel aquifers associated with alluvial deposits 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 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.

AQUIFERS SUITABLE FOR ATES

Data gathered on aquifers in Region 10 indicate that there are many aquifers throughout the region which may be suitable for ATES. The data provided in Table 10-2 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 which aquifers are suitable for ATES is organized according to the geologic age and character of the major aquifers found in Region 10. Those aquifers considered suitable for ATES are listed in Figure 10-9.

CRETACEOUS- AND TERTIARY-AGED AQUIFERS

Throughout Region 10, with the exception of the area from New York (Long Island) to Massachusetts, there are major aquifers associated with sand and gravel deposits that are Cretaceous and Tertiary in age. The aquifers are associated with the stratigraphic formations listed in Figures 10-5, 10-6 and 10-7. The general geologic and hydrogeologic framework of these aquifers has been provided in previous sections of this chapter. Aquifers of pre-Cretaceous age, found on the periphery of the Mississippi Embayment, do not meet the minimum yield requirement of 50 gallons per minute (Boswell et al. 1965) and therefore, according to the scope of this study, cannot be considered suitable for ATES.

Because the aquifers of Cretaceous and Tertiary age have been widely developed for drinking water supplies, and because of extensive

AQUIFER	TYPES OF A.T.E.S. STORAGE	COMMENTS
Cretaceous and Tertiary Sands and Gravels (Gulf and Atlantic Coastal Plains)	Small system - high, low, chill storage Large system - high, low, chill storage	Owing to variable conditions within each aquifer, these sand and gravel aquifers may be suitable for all types of A.T.E.S. storage, depending upon the conditions at a particular location. The transmissivity values for these aquifers are often in excess of 1,000,000 gpd/ft., which are generally considered undesirable.
Widespread Outwash Deposits (South of the Mississippi Embayment and Long Island)	Large system - high, low, chill storage	Wells finished in these aquifers are generally capable of yielding greater than 500 gpm and the aquifers are usually confined. Several of the aquifers report transmissivity values in excess of 1,000,000 gpd/ft., which are generally considered undesirable.

MAJOR AQUIFERS SUITABLE FOR A.T.E.S. IN REGION 10

FIGURE 10-9

oil and gas exploration along the Coastal Plain and continental shelf, these aquifers have been widely studied and abundant data have been generated. Table 10-2 provides some of the most reliable data found in the literature for these aquifers.

Scrutiny of the data in Table 10-2 reveals that the geologic and hydrogeologic characteristics do vary markedly across the extent of the aquifers. Some of the factors causing the variability are facies changes, depth, and degree of confinement. However, in general, the aquifers do fall within the guidelines of being suitable for ATEs over most of the area of Region 10. It should be noted that the transmissivity values for many of the Cretaceous and Tertiary aquifers are quite high, often in excess of 100,000 to 200,000 gallons per day per foot. The consequences, with respect to thermal energy storage, of such high transmissivity values are not known at this time; however, such high values are considered undesirable.

The variable hydrogeologic characteristics of all the Cretaceous and Tertiary aquifers indicate that the aquifers may be suitable for all types of storage (i.e. small system chill, low or high temperature storage; and large system chill, low or high temperature storage) depending upon the hydrogeologic conditions at a given location. It is recommended that site-specific information be generated prior to evaluation of the ATEs potential at a particular location.

QUATERNARY-AGED AQUIFERS

As previously discussed in this chapter, there are widespread, buried outwash deposits in southern Louisiana, southeastern Texas, and

Long Island. In each of these localities three major outwash formations stratigraphically separated by marine silts and clays are generally found. The marine silts and clays provide confinement for the aquifers associated with the outwash.

The aquifers associated with the outwash deposits appear to have excellent potential for ATES. Data for three outwash layers in southern Louisiana are provided in Table 10-2. In southern Louisiana, these outwash layers are referred to as the "200-foot sand", the "500-foot sand", and the "700-foot sand" (Harder 1960; Jones 1956; and Meyer and Turcan 1955). The data indicate that these aquifers may all be suitable for large system, high temperature storage. However, transmissivity values for the "200-foot sand" and the "500-foot sand" are in excess of 100,000 gallons per day per foot (Harder 1960). It is recommended that site-specific information be developed prior to an evaluation of the outwash aquifers' suitability for ATES.

REGION'S ATES POTENTIAL

Throughout most of Region 10 there are aquifers with potential for thermal energy storage. The aquifers in the Gulf and Atlantic Coastal Plain showing the most promise are: 1) the Cretaceous and Tertiary sand and gravel deposits, which may be suitable for all types of storage owing to the great variable hydrogeologic characteristics of these aquifers; and 2) the buried outwash deposits of southern Louisiana, southeastern Texas, and Long Island, which may be suitable for large system, chill, low and high temperature storage. In all cases, site-specific information is needed before determining the ATES potential of a particular location.

In the Transition and Florida Coastal Plain, most of the major aquifers are associated with limestones and are therefore not suitable for ATES. However, a major aquifer (Tuscaloosa Formation) associated with sandstones of Cretaceous age is found at the Fall Line. The aquifer may be suitable for large system, chill, low and high temperature storage, but site-specific information is needed to assess the ATES potential at a given locality.

Owing to the regional scope of this study, only the regional aquifers of Region 10 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 ATES potential 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.

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Region 11. Hawaii

REGION 11 - HAWAII

INTRODUCTION

The state of Hawaii comprises the eleventh ground-water region in the ATES study. The eight main islands at the southeastern end of the Hawaiian Archipelago are the main land masses in Region 11. The eight islands are as follows: 1) Hawaii; 2) Maui; 3) Lanai; 4) Kahoolawe; 5) Molokai; 6) Oahu; 7) Kauai; 8) Nihau. The Hawaiian Archipelago, to which these islands belong, is made up of shoals, reefs, and islands stretching approximately 1,500 miles in a northwest to southeast direction across the Pacific Ocean. The main islands lay between longitudes 155° to 163° west and latitudes 19° to 23° north.

The average annual rainfall for the islands ranges from less than 35 to 100 inches per year. Since most of the rainfall is orographic, the local mean rainfall for the larger islands ranges from less than 20 to more than 300 inches per year. Rainfall is the principal source of ground-water recharge and its distribution and quantity are important in understanding the extent and quality of groundwater for the Hawaiian Islands. The largest portion of rainfall is attributed to the moist tradewinds and generally falls at the higher elevations. The non-tradewind rainfall occurs in short, infrequent storms at lower elevations and on the open ocean; the total quantity of precipitation is small and its contribution to ground-water recharge is generally insignificant.

The future water demands of the Hawaiian Islands will be best met by the ground-water resources rather than surface water resources.

The easily developed surface water supplies have been developed and are fully utilized. Future development of the surface water supply will often be cost prohibitive. For these reasons, groundwater in Hawaii is a valuable resource and in the future will represent the largest percentage of the total water supply. As a whole the water resources of the Hawaiian Region are greater than the foreseeable water demand (Takasaki 1978). On an individual basis each island must have an independent water supply and the water resources of each island vary widely. A major portion of the water supply variability can be attributed to the islands' geology, which affects the amount of fresh water rainfall it receives and how well it stores this water.

GEOLOGIC FRAMEWORK

The Hawaiian Islands are the tops of shield volcanoes whose domes rise from the ocean floor. Each island consists of one to five of these domes which are composed of thousands of basaltic and andesitic lava flows. The oldest island is Kauai, in the northwest; the youngest and largest is the island of Hawaii located at the southeast end of the chain. The lava forming these domes was forced to the surface in repeated flows from narrow zones of fissures (dikes) associated with each volcano. The lavas were first extruded below sea level resulting in very rapid cooling and producing dense, massive flow zones with low permeability. As the domes reached sea level and above, the lavas flowed more freely, cooled more slowly, and produced thinly bedded, ropey and blocky flow zones with high permeability. The continuous lava extrusions produced great mountain masses which eventually were lowered in isostatic equilibrium. Consequently, the highly permeable lava flows, which were

originally extruded above sea level, now extend great distances below sea level. The highly permeable sequence of lava flows comprises the principal ground-water reservoirs of the Hawaiian Islands (Takasaki 1978).

The origin of the Hawaiian Islands is the same for all eight islands and therefore the geologic framework as described above is nearly identical for all of the islands. The geologic similarities between islands results in nearly identical hydrogeologic environments which are discussed next.

HYDROGEOLOGIC FRAMEWORK

Since the Hawaiian Islands all have a similar geologic framework, the discussion in this section will be general and applicable to the occurrence of groundwater for all islands. The principal ground-water reservoirs and therefore the hydrogeologic environments are the highly permeable lava flow zones consisting of lava types known locally as "aa-aa" and "pahoehoe". The subsurface portion of these flows often extends to depths greater than 1,000 feet below sea level and are also found at high altitudes on the mountain slopes (Takasaki 1978).

Two distinct hydrogeologic environments exist for these permeable lava flow zones (Takasaki 1978). The first consists of interconnected saturated flow zones in which the groundwater is impounded behind impermeable dikes within the more permeable flow zone. The interior of the islands, in particular along the higher slopes of the volcanic domes, contain these types of reservoirs. Groundwater occurring in this environment is referred to as dike-impounded water or dike-impounded

reservoirs. These types of reservoirs have anomalously high ground-water gradients and high hydraulic heads. Recharge to the impounded reservoirs is from the large amounts of rainfall falling on the high slopes where these reservoirs are located. Natural discharge is largely from springs feeding mountain streams and leakage to the basal reservoirs. Because rainfall is a sole source of recharge, the main impounded reservoirs are located on the windward side of the higher slopes.

Some of the more common dike-impounded reservoirs and their locations are as follows: the Schofield water body, Koolau Volcanic Series, central Oahu; Mauna Loa lavas, Hawaii; west Maui lavas, Maui; east Molokai Volcanic Series, Molokai; Waianae Volcanic Series, west Oahu; Lanai Volcanic Series, Lanai. The impounded reservoirs represent a major fresh-water supply source for the Hawaiian Islands. The large amounts of storage in these reservoirs and their isolation from saline water makes them most attractive for future development.

The second hydrogeologic environment consists of interconnected reservoirs that are in dynamic equilibrium with the underlying saline groundwater. These reservoirs are located at the lower elevations and along the outer rims of the islands. The water-bearing rock formations are the same highly permeable, thinly bedded lava flows common to the dike-impounded reservoirs.

The main distinction is that at lower elevations the water bearing rock is at the lower portion of the lava flows remote from the lava source area, and the ground-water flow is much less affected by the impermeable dikes. Ground-water in reservoirs of this type is referred to as a basal water and represents a highly fugitive but renewable

resource. Since this water is in dynamic equilibrium with the underlying saline water, excessive withdrawals from basal reservoirs result in saltwater intrusion. Additionally, the quality of groundwater in the basal-reservoirs is naturally less than that of the dike-impounded water because the basal reservoirs are a greater distance from the recharge areas along the mountain slopes. An undetermined volume of recharge to the basal aquifer is attributed to leakage from the dike-impounded reservoirs, which are located upgradient. Other recharge to the basal aquifer comes from irrigation return flow that is also slightly lower in quality than the rainfall recharge of the dike-impounded reservoirs. The infiltration of stream flow across the lowlands also attributes to the basal recharge, and it is known that peak stream-flow volumes represent additional recharge potential. This is particularly true for the heavily used basal aquifer in the Pearl Harbor area where artificial recharge with stream flow has been considered (Hirashima 1971-A).

Discharge from the basal aquifer is normally into the sea along the shore line at or below sea level. This flow is very diffuse and generally cannot be measured. The overall ground-water gradient is toward the sea and therefore the major discharge area is to the sea. In some areas the seaward ground-water movement is blocked by sedimentary caprock, resulting in artesian pressures and allowing discharge from springs well above sea level. This is the case in the Pearl Harbor area where spring discharge varies directly with static water level in adjacent artesian wells (Visser and Mink 1964; and Hirashima 1971-A). Some of the more common basal reservoirs are as follows: Kohala Mountain lavas, northern Hawaii; Mauna Kea lavas, southern Hawaii; west Maui

lavas, Maui; Haleakala lavas, central Maui; east and west Molokai Volcanic Series, Molokai; Koolau Volcanic Series, eastern Oahu; Waianae Volcanic Series, western Oahu; Napali Formation, Kauai.

The basal reservoirs have been extensively developed (except in northern Hawaii) for irrigation and domestic use and therefore they are the source for most current water supplies. Early development for agricultural use has produced concentrations of pumping wells in small areas, causing excessive local drawdowns resulting in some localities having a lower quality water because of saline water intrusions. The future use and development of the basal reservoirs is limited by the adverse effects of past development and by present land use.

MAJOR AQUIFERS

The selection of major aquifers within region eleven was based primarily upon the present use of a particular ground-water reservoir (Figure 11-1). This method was used because the vast majority of available ground-water data pertains chiefly to quantities used and place of use. Additionally, many of the dike-impounded reservoirs are tapped by tunnels and therefore the aquifer characteristics, normally determined by pump test data analysis and used for aquifer selection, are unobtainable. The aquifers listed in this section represent the ground-water reservoirs with the highest current use and are somewhat biased towards the islands with the most available data. Table 11-1 provides a listing of the major aquifers of Region 11. Data pertaining to each of the aquifers are presented in Table 11-2.

NAPALI BASAL

The Napali basal ground-water reservoir consists of basaltic lavas of the Napali Formation and is found on the island of Kauai at the northwest end of the Hawaiian chain. The major use of this reservoir is for irrigation on the western side of Kauai where approximately 32 million gallons per day are withdrawn. On the eastern side of the island the Napali Formation consists of thick basal reservoirs of excellent ground-water quality. Central Kauai contains a part of the Napali Formation which has high water levels from impoundment by the surrounding Koloa Volcanic Series. This central portion has the islands second highest withdrawal rate of approximately 12 million gallons per day; this estimate includes some of the dike-impounded groundwater from the Koloa Volcanic Series.

MAJOR AQUIFERS IN REGION II

FIGURE II-1

MAUNA KEA BASAL

The Mauna Kea lava flows are located on the large island of Hawaii at the southeast end of the Hawaiian chain. These lavas cover the northern and eastern portions of the island and are the major source of the 18 million gallons per day withdrawal from the basal reservoir on the eastern side of the island. Their major use is for irrigation of sugar cane and other crops.

HALEAKALA BASAL

The Haleakala lavas form a large and extensively used basal ground-water reservoir in central Maui. Approximately 170 million gallons per day are withdrawn from this reservoir and used primarily for sugar cane irrigation on the lower eastern slopes. The quality of groundwater from the Haleakala basal reservoir is lower in the heavily pumped western area but improves towards the east. A large amount of recharge (90 million gallons per day) is from irrigation return flow.

PEARL HARBOR BASAL

The basal ground-water reservoir underlying the Pearl Harbor area is extensively developed for municipal, agricultural and industrial use. This ground-water reservoir is much larger than other similar basal reservoirs and has an areal extent of over 100 square miles in southern Oahu and underlies the entire Pearl Harbor area eastward to Honolulu. This reservoir is unique because it has a sedimentary caprock on the seaward end, which confines the groundwater and prevents the usual seaward flow. The net effect of caprock is the artesian pressures common to wells in this area. The basal reservoir contains several different compartments identified by different static water levels. The

basal aquifer is composed of the highly permeable basaltic lava flows of the Koolau Volcanic Series and some of the Waianae Volcanic Series on the extreme west side. These lava flows extend thousands of feet below sea level and are permeable to great depths. Rainfall in the Koolau Range is the principal source of recharge to the basal aquifer; this recharge is temporarily stored in the dike-impounded reservoirs of the Koolau Range. A significant part of the nearly 260 million gallons per day withdrawn from this aquifer is used for irrigation and the return flow contributes approximately 12 million gallons per day to the total recharge. The discharge is from the withdrawals and, because of the confining caprock, the Pearl Harbor springs. The discharge from the springs has averaged 80 million gallons per day from a narrow zone about 20 feet above sea level. Additional springs were likely to exist prior to lowering of the basal head by approximately 30 feet in 1889 (Visser and Mink 1964). Some discharge occurs just at or below sea level along the coast line but this is very diffuse and is not measurable. The estimates for volumes withdrawn include some water from the dike-impounded Schofield water body to the north.

NORTH CENTRAL OAHU

The ground-water reservoir of north central Oahu is contained within the Koolau volcanic series in the high central plateau region between the Koolau and Waianae Ranges. This dike-impounded reservoir is known as the Schofield water body. The central position of the Schofield water body is such that it has been developed to serve both the northern and southern portions of Oahu. The development of this water body has been at the expense of reduced recharge to the basal

reservoirs in southern Oahu (Pearl Harbor) and in the Waialua area of northern Oahu.

WAIANAE VOLCANICS

The Waianae Range in western Oahu contains a dike-impounded ground-water reservoir within the Waianae Volcanic Series. This dike-impounded reservoir receives low recharge owing to the rain shadow effect of the larger Koolau range and Waianae's position on the leeward side of the moist trade winds. The development of this ground-water reservoir is primarily for agricultural use and approximately six million gallons per day are withdrawn. An additional two million gallons per day are imported and recharge is low because of the high evapotranspiration rate from the shallow groundwater level. Minor withdrawals are made from a small basal reservoir in this area but the water quality is generally poor compared to the excellent quality of the dike-impounded water.

KOOLAU RANGE

Groundwater impounded by dikes in the Koolau Range is a major water supply source for eastern Oahu and has been developed to bring some to the leeward side of the range. The Koolau Range is an erosional remnant of the Koolau volcanic dome which contains a rift zone extending in a northwesterly, southeasterly direction for approximately 30 miles. The many vertical dikes are parallel to the rift zone and are spaced only a few feet apart in the northwestern end and much more widely spaced on the southwestern side. The dikes are considerably less permeable than the intruded rock and form the walls for hundreds

of elongated ground-water reservoirs. Precipitation along the crest of this range reaches 300 inches per year, which supplies abundant recharge. The tunnels tapping these reservoirs withdraw ground-water volumes varying from 40 to 50 million gallons per day. The use is for both municipal and agricultural, with agricultural being dominant. Where the dike-impounded reservoirs have been breached by stream erosion, the groundwater contributes to stream flow. Prior to development by tunnels the groundwater moved along the strike of the impounding dikes to the lower elevations; this movement occurs now but at slower rates and with a much reduced volume from the depletion of storage in many of the dike-impounded reservoirs.

AQUIFERS UNSUITABLE FOR ATES

All of the major aquifers of Region 11 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 11-2 provides a listing of the major aquifers in Region 11 are considered unsuitable for ATES.

Groundwater in Region 11 occurs in two distinct hydrogeologic environments. Although the lithology for each environment is nearly identical, the factors controlling the movement, availability and quantities of groundwater are unique to each environment. As discussed earlier in this report, the two environments are the dike-impounded ground-water reservoirs and the basal ground-water reservoirs. The major aquifers for each of the Hawaiian Islands are either basal or dike-impounded and their ATES potential will be discussed with respect to these two hydrogeologic environments.

The dike-impounded reservoirs of Region 11 have anomalously large hydraulic gradients, limited areal extent and closely spaced boundary conditions. Additionally, the horizontal and vertical permeabilities differ tremendously and vary widely from one point to another within one reservoir. Flow structures within the aquifer matrix are another undesirable feature. There are frequent and irregular openings between the surfaces of lava flows, the lava tubes in the pahoehoe flows, the clinker layers in the aa flows and many joint patterns formed during

AQUIFER	REASONS FOR UNSUITABLE RECOMMENDATIONS	COMMENTS
Dike Impounded Reservoirs - North Central Oahu - Waianae Volcanics - Koolau Range	Large hydraulic gradients, limited areal extent, permeabilities, and fracture porosities.	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.
Basal Reservoirs - Napali Basal - Mauna Kea Basal - Haleakala Basal - Pearl Harbor Basal	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 II

FIGURE II-2

the lava's cooling. These features act to control the ground-water flow regime resulting in a flow system of such complexity that in some instances the standard pumping test analyses do not apply to Hawaiian aquifers. In general, the dike-impounded reservoirs are tapped by large-diameter tunnels and standard aquifer parameters are not available. For these reasons, the dike-impounded reservoirs of Region 11 are considered unsuitable for ATES.

The basal reservoirs of Region 11 possess all the undesirable flow structures common to the dike-impounded reservoirs. Since the basal reservoirs include the front of the lava flows, the flow structures are often more pronounced and have thicker interflow zones. The resulting differences between the horizontal and vertical permeability are desirable. However, the naturally high permeabilities are undesirable. Groundwater within these reservoirs is in dynamic equilibrium with the underlying sea water, which provides poor thermal insulation. Also, there may be a problem with the chemical compability between the saline water and injection fluid. The basal reservoirs of the Hawaiian Islands possess a unique combination of anisotropy, heterogeneity and fracture porosities resulting in their flow systems being considered unsuitable for ATES development.

REGION'S ATES POTENTIAL

Overall, the ATES potential of Region 11 is very low. Owing to the fact that groundwater occurs within the lava flow zones and is controlled by the highly variable flow structures and fracture porosities, the Hawaiian Islands have essentially no potential for ATES development.

The current research on the Hawaiian Islands relates primarily to the storage depletion problems of the dike-impounded reservoirs, the problem of sea-water intrusion, and the proper development and distribution of ground-water supplies to the drier, leeward areas. Studies of ground-water modeling for determining pumping and injection well effects on the freshwater-saltwater transition zone may be useful but will most likely document those characteristics of the Hawaiian aquifers that are undesirable for ATES development.

Owing to the regional scope of this study, only the regional aquifers of Region 11 were considered for ATES potential, and only the most recent and available literature was reviewed. Site-specific information may possibly prove that the aquifers cited above have potential for ATES at particular localities. The purpose of this regional study is to determine which aquifers appear to have the greatest potential for ATES and therefore should not preclude site-specific investigations.

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Region 12. Alaska

REGION 12 - ALASKA

INTRODUCTION

Alaska comprises the twelfth and last ground-water region. Being separate and very different from the remaining contiguous forty-eight states, it was natural to assign this state an independent ground-water region. This region is contained entirely within the boundaries of one state and will herein be referred to as Alaska rather than by region. Alaska is certainly America's last remaining true wilderness; that is, an area about which there are many unknowns. Specifically, the ground-water resources of Alaska are not well known. Many of Alaska's unknowns can be attributed to the vast land areas that are either uninhabited or uninhabitable.

Alaska's great geographic extent covers approximately 586,412 square miles and spans latitudes 54° to 71° north and longitudes 130° to 172° west. This results in four distinct climatic zones for the state. Divided on the basis of temperature and precipitation the four zones are as follows: 1) arctic; 2) continental; 3) transition; 4) maritime. The mean annual temperature ranges from -12° C in the arctic zone to 7° C in the maritime zone. Recorded annual precipitation ranges from about 5 to 300 inches along the south coast within the maritime zone.

Except in the maritime zones of south central and southeastern Alaska, the subfreezing air temperatures cause precipitation to fall as snow for six to nine months of the year and even year-round in the high mountain regions. Therefore, the rate of occurrence of hydrologic events and their distribution in time differs greatly from other regions.

The progression of hydrologic events most often occurs in a flurry of hydrologic activity concentrated in a short summer period after many months of hydrologic dormancy.

The early, limited developments and settlements in Alaska created few water resource problems. However, the steady growth of population and development since World War II created some critical water supply needs and problems. The concern for water resources is a partial result of heavy local use of Alaska's surface water resources. Although Alaska contains extensive lakes and streams, surface water is a limited resource because many streams are frozen and most contain glacial silt making them unacceptable for human use. These factors lend special significance to groundwater as a water supply source for this state.

Groundwater is an untested resource of Alaska and its potential development exceeds current use in most locations. A few detailed hydrologic studies have been made in and around areas of major population centers such as Anchorage and Kenai and at some of the larger settlements along the state's limited highway system. However, there are still large areas where data are insufficient to allow more than just a general evaluation of the water resource potential. The inevitable future development of Alaska's mineral wealth and forestry, fishery, and agriculture will create great demand for water. This will most likely result in many new and detailed ground-water studies because of the limited surface water supply. The increased interest in groundwater will hopefully provide specific hydrogeologic data and allow for a more thorough evaluation of Alaska's ground-water resources.

GEOLOGIC FRAMEWORK

Alaska's geologic framework can be compared to that of western Canada and the western United States. Major landforms include: 1) three great mountain ranges, the Brooks, Alaskan and Coastal; 2) a broad interior lowland drained by large rivers and containing scattered highlands and plateaus; 3) large coastal plains, valleys, and river deltas. The mountain ranges and nearby uplands are generally mantled by the glacial drift from Pleistocene Epoch glaciers which originally occupied these highlands. The older rocks occupying the vast interior valleys and large areas of the interior lowland are generally covered by outwash deposits extending beyond the limits of former glaciers or by sedimentary material of alluvial origin.

The landforms comprising the coastal plains, valleys and river deltas of Alaska reflect various combinations of depositional environments. The coastal plains and river deltas represent the constructional shoreline features formed primarily from shallow water deposits of marine sediments and freshwater deltas. The coastal basins and valleys, whose basic configurations were produced chiefly by structural or erosional forces, now primarily consist of sediments derived from marine deposition and material from glacial and alluvial sources. These landforms are inherently related to the hydrogeologic environments of Alaska.

HYDROGEOLOGIC FRAMEWORK

In Alaska, the following four generalized hydrogeologic environments are recognized (Williams 1970): 1) alluvium of river valleys, including the flood plains, terraces, and alluvial fans found in the uplands

and in both the major valleys and the mountain valleys; 2) glacial and glaciolacustrine deposits of the interior valleys; 3) coastal-lowland deposits; 4) bedrock of the upland and mountains. With the exception of the coastal-lowland deposits, the ground-water flow systems of these environments are influenced and modified by permafrost conditions.

The occurrence of groundwater in Alaska is closely allied to the geologic and physiographic framework and is influenced by the distribution of permafrost in all but the south coastal regions (Zenone and Anderson 1978). The effects of permafrost on groundwater decrease progressively from the continuous permafrost zone of northern Alaska to the southern limit of permafrost (Figure 12-1). In the continuous permafrost zone the sediments are almost entirely frozen to depths as great as 2,000 feet. Groundwater is usually present below the base of permafrost or, locally, above permafrost at places where conductive heat flow from surface water bodies lowers the upper surface permafrost below the depth of seasonal freezing. Groundwater may also exist above permafrost in perched water table conditions. In the discontinuous permafrost zone, the frozen ground is warmer than in the continuous permafrost zone and large, interconnected, and extensive unfrozen areas are present. However, even within this zone of "warm" permafrost its local distribution is determined largely by subsurface drainage and surface insulation. These factors are in turn controlled by the physiographic conditions of slope, geologic materials and vegetation cover.

In general, permafrost affects nearly all aspects and characteristics of groundwater (Zenone and Anderson 1978). The vast thicknesses of frozen groundwater serve as impermeable boundary layers that control the movement of groundwater and also serve to reduce recharge. Within

REGION 12 GENERALIZED DISTRIBUTION OF
PERMAFROST

FIGURE 12-1

the continuous permafrost zone, the permafrost areas effectively reduce the amount of permeable ground available for ground-water storage. The repeated freezing and thawing of the ground affects ground-water quality and in many areas sub-permafrost groundwater has a high dissolved solids concentration and relatively high mineralization. Within the discontinuous permafrost zone the low permeability of frozen ground lying beneath the active, freeze-thaw layer restricts recharge and effectively isolates the near surface system from the regional subpermafrost layers.

In summary, the special characteristics of the Alaskan hydrogeologic environment, as well as other arctic and subarctic areas, result from the influence of climatic conditions on the physical state (solid or liquid) of water and from the climatic effects on its rate of movement through the hydrogeologic system. In the following brief description of the four hydrogeologic environments, the detailed effects of permafrost and its modifying role in the ground-water flow regime are not discussed.

ALLUVIAL DEPOSITS

Of the major hydrogeologic environments in Alaska, the alluvium of river valleys, including flood plains, terraces, and alluvial fans of major valleys, upland valleys and the smaller mountain valleys, contain the greatest volume of groundwater in storage. Alluvial deposits also have the greatest recharge potential because they are often in hydraulic connection with the extensive surface water drainage systems. The major ground-water and surface water systems belong to the Yukon, Tanana, Kuskokwim, Kobuk and Susitna Rivers and their associated basins. The alluvium generally consists of sand, gravel, and silt. The flood plains, low terraces, and alluvial fans consist primarily of silt;

sand and gravel are found in minor amounts. Recharge to and discharge from the alluvial aquifers takes place chiefly along stream channels and through lake beds overlying permeable alluvial deposits.

GLACIAL AND GLACIOLACUSTRINE DEPOSITS

The glacial and glaciolacustrine deposits of interior valleys consist largely of till deposited during Pleistocene time. As the glaciers advanced from the major mountain ranges into the interior plains and lowlands, they often covered proglacial lakes, so that beds and lenses of clay, silt, sand and gravel were interbedded with the till. During the retreat of glaciers, the till was covered by permeable water-worked deposits, some of which were buried by the till of later glacier advances. The sediments and deposits of till are predominately fine-grained. The largest deposits of glacial and glaciolustrine sediments are in the Copper River lowland. The southern Brooks Range and the Alaska Range contain less glacial deposits. These widely distributed deposits have not been subjected to significant ground-water exploration and because of their fine-grained nature, probably do not contain major aquifers, excepting those deposits in southern Alaska where permafrost is either absent or occurs in isolated masses.

COASTAL LOWLAND DEPOSITS

Alaska's coastal lowland deposits represent combinations of several depositional environments. The variety of environments are of two general types; they include shallow-water constructional features such as the coastal plains, deltas, bars, spits, beaches and the coastal basins

and valleys whose structural and erosional controlled configurations have since been filled in by sediment from marine and non-marine sources.

Coastal Plains

The coastal plain sediments are the most extensive of the coastal lowland deposits. Alaska's coastal plains are located in three general areas: 1) the Arctic coastal plain; 2) the coastal plains of the Seward Peninsula near Nome; and 3) along the Gulf of Alaska, primarily from the Copper River southeast to the city of Yakutat. In all three areas the sedimentary deposits consist primarily of silt, sand and minor gravel. In the north and northwestern areas the deposits are generally of marine origin. Permafrost has a major role in limiting the ground water availability in the north and northwestern area. The discontinuous coastal plain in the southeast, along the Gulf of Alaska, contains alluvial, glacial, marine, and beach sediments which vary to predominantly fine-grained glacial sediments at Yakutat. Permafrost is absent in the area but the availability of groundwater is limited by the fine-grained deposits and their limited areal extent.

Ground-water occurrence and movement in the coastal plain deposits is controlled by permafrost in the north and northwestern coastal plain (Zenone and Anderson 1978). Permafrost reaches a depth of 2,000 feet in the Arctic plain at Prudhoe Bay. At Nome, the ground-water storage is limited by thick permafrost layers. In all coastal plain areas the thickness of the freshwater aquifers is determined by the freshwater-saltwater interface and is probably quite thin because of low relief and the close proximity to saltwater. The presence of predominantly fine-

grained sediments restricts the withdrawal of groundwater and is the major limiting factor in the basence of permafrost.

Deltas

A large part of the coastal lowlands in northern and northwestern Alaska are formed by the large river deltas of the Colville, Noatak, Kobuk, and Selawik Rivers and the compound delta of the Yukon and Kuskokwim Rivers. In the south central and southeastern parts of Alaska smaller river deltas are formed by several other rivers; the largest of these is the Copper River delta. Subsurface data are available for the Yukon, Kuskokwim and Copper River deltas. The sediments of the major river deltas consist of sand, silt, and thin beds of gravel. The Yukon-Kuskokwim deltaic sediments are nearly 1,000 feet thick at the site of an exploratory oil well near Bethel. A comparison of river stage and ground-water levels at Bethel suggest there is a hydraulic connection between the river and ground-water system. There exists a tremendous potential for induced ground-water recharge from stream flow if the sediments of major deltas are in hydraulic connection with their associated rivers. However, the movement of groundwater and its availability is extremely limited by the predominately fine-grained sediments and by the confining boundaries imposed by thick permafrost layers. In addition to this, the thickness of any freshwater aquifer is determined by its relationship to the freshwater-saltwater interface, which is probably a major limiting factor near the edges of these coastal deltas.

Shallow Water Deposits

The depositional forms of bars, spits and beaches border the entire coastline of Alaska. They contain very small amounts of ground water. The groundwater in these depositional environments occurs in very shallow layers and is restricted by the freshwater-saltwater interface. Along the Gulf of Alaska coastline, the abundant recharge from precipitation favors the occurrence of shallow groundwater in the permeable coastal sediments. In the north and northwestern areas the shallow coastal ground-water supplies are often obtained from perched aquifers above the permafrost (Williams 1970).

Coastal Basins and Valleys

The deposits of the coastal basins and valleys consist primarily of glacial till interbedded with sands, silt, clay and gravel of fluvial and marine origin. The major coastal basins and valleys are found at the following locations: Resurrection Bay; Bristol Bay; Cook Inlet; along the Gulf of Alaska near Valdez; and in smaller valleys and basins located along the far southeastern coast of Alaska.

The best known coastal deposit is the Cook Inlet lowland, particularly near the Anchorage area. Here the sediments are known to be predominantly glacial till interbedded with fine-grained glaciolacustrine deposits and some water-worked deposits of sand and gravel. In some instances the fine-grained deposits serve as confining layers to ground-water flow, producing the artesian aquifer of the Anchorage area. The Bristol Bay lowlands are assumed to have deposits and ground-water environments similar to those of the Cook Inlet lowland. However, at Bristol Bay, permafrost has a more controlling effect on ground-water

movement and storage. Permafrost at Bristol Bay averages 175 feet thick (Williams 1970).

At Resurrection Bay the sediments consist of glacial till, glacial-fluvial sand and gravel, marine deposits of fine-grained sand and silt, and stream-deposited sand and gravel. The Resurrection Bay deposits are estimated to be 1,000 feet thick. In the area of Seward, confined and unconfined ground-water conditions are present within the alluvium of the Resurrection River and in the mountain-front alluvial fans. The shallow, unconfined ground-water body is recharged primarily from stream flow losses through the sand and gravel deposits of the alluvial fans (Dearborn, Anderson and Zenone 1979).

Along the Gulf of Alaska coast, near Valdez, groundwater conditions are assumed to be similar to those at Resurrection Bay. However, the unconsolidated sediments at Valdez are estimated to be 600 feet thick. In both cases, the freshwater aquifers are confined beneath marine deposits of silt and clay and contained in the alluvial deposits at the heads of fiords.

The alluvium-filled coastal valleys in the mountainous southeastern Alaska coastal area are generally much smaller than those mentioned above. One of the more favorable areas may be the ground-water reservoir in the Mendenhall River valley near Juneau where the unconsolidated sediments may be 700 feet thick (Barnwell and Boning 1968). However, this area has a very limited areal extent of approximately 25 square miles.

The recharge rates to coastal valley deposits are assumed to be high because, as in the Cook Inlet and Resurrection Bay lowland area, streams crossing the basin lose a large part of their flow to the ground-water system. At the periphery of the basins, recharge is from pre-

cipitation and snow melt infiltration. Often, the deeper aquifers are recharged by moving along the alluvium-bedrock interface. The volume of freshwater within these deposits is not known, but is probably somewhat limited by the freshwater-saltwater interface. Ground-water discharge augments stream flow during summer and maintains minimum flow during winter months.

BEDROCK

In approximately 75 percent of Alaska, glacial and alluvial deposits are thin, have low permeability, or are absent. In such areas, appreciable amounts of groundwater occur only in aquifers consisting of consolidated rock. The four general types of bedrock aquifers are as follows: 1) carbonate rocks; 2) clastic sedimentary rocks; 3) volcanic rocks; and 4) metamorphic and intrusive igneous rocks.

Carbonate Rocks

The most extensive and best known carbonate rock deposits are those of the Brooks Range in the far north-central portion of Alaska. The ground-water movement in these rocks has developed solution cavities and conduits through which the water flows to the surface, creating many springs. Conclusions concerning the occurrence and movement of groundwater in the carbonate rocks of the Brooks Range are inferred from measurements and observations of spring flow in both the eastern Brooks Range and in parts of the western Brooks Range. Although carbonate rocks are quite extensive in the mountain ranges of southeastern Alaska, they have not been explored and utilized there as a water source.

Clastic Sedimentary Rocks

Sandstones and alternating strata of indurated sand, silt, and clay are widespread throughout the state. Although these deposits have been extensively explored for oil, gas, and coal, little hydrologic data has been recorded. In the Gulf of Alaska area the Kenai Peninsula has been explored to determine the ground-water resources there. As expected, the Kenai Formation, consisting of indurated siltstone and sandstone, is a poor aquifer because of its extremely low permeability. Very low well yields are reported and the water is sometimes of poor quality. However, near Homer, the Kenai Formation is used as a municipal and industrial water supply with yields varying from 50 to 80 gallons per minute (Waller, Feulner and Morris 1968).

Volcanic rocks - Volcanic rock in Alaska is especially prevalent in some areas of the southwestern portion of the state. The Aleutian Chain, the Alaskan Peninsula, the Seward Peninsula and the Wrangell Mountains contain extensive volcanic formations. The occurrence of groundwater in volcanic rocks is highly variable, and only a few wells are known to produce water from them. On some islands in the Aleutian Chain the volcanic rocks have great permeability resulting from the interlayering of vesicular flows and gravel interbeds. On the islands, the groundwater is limited primarily because the extremely high permeability allows easy discharge of the freshwater to the sea. However, the basalt lava flows in the mountains and uplands on the northern Seward Peninsula may be a potential ground-water source (Dearborn, Anderson and Zenone 1979).

Metamorphic and igneous rocks - Metamorphic and igneous rocks comprise the cores of the principal mountain ranges of Alaska. The secondary porosities of faults and fractures are responsible for the occurrence of groundwater. In some areas of Kodiak Island, a fractured slate is known to have a yield of approximately 50 gallons per minute; elsewhere wells in such rocks produce less than 10 gallons per minute. The most intensively developed bedrock aquifer is in the uplands northeast of Fairbanks, where a fractured schist produces minor amounts of groundwater. In general, groundwater is present only in weathered zones at the bedrock surface and in a few locations containing fractures. Below a depth of approximately 300 feet these zones of secondary porosity diminish rapidly and many deep wells are reported to be dry.

MAJOR AQUIFERS

For the purposes of this study, a major aquifer is defined as one with significant areal extent that can sustain yields of at least 50 gpm throughout its extent. The aquifers within Alaska that meet these requirements are presented in the following paragraphs and discussed with respect to their location, lithology and approximate areal extent (Table 12-1). Specific data and the data source are provided for each major aquifer in Table 12-2.

RESURRECTION BAY

Surrounding the town of Seward on the western side of Resurrection Bay and extending northward to the head of the valley is an alluvial valley capable of large ground-water yields. Both confined and unconfined ground-water conditions are present within the unconsolidated Pleistocene alluvial deposits. The thickness of these deposits is estimated at 1,000 feet; however, most wells tap aquifers at depths between 200 to 400 feet below land surface (Dearborn et al. 1979). Recharge to the unconfined aquifer is primarily from stream flow losses in the river valley and across the alluvial fans. For the confined aquifer, recharge is from precipitation and snow melt infiltration at higher elevations. The degree of confinement and integrity of the confining layer is questionable because several recharge boundaries were noted in pump tests and drawdowns in observation wells were not as expected (Dearborn, Anderson and Zenone 1979). The areal extent is estimated at slightly less than 30 square miles; this estimate was made from a geological map.

ANCHORAGE

Alaska's best known ground-water system is contained within Cook Inlet adjacent to the city of Anchorage (Figure 12-2). This system will herein be referred to as the Anchorage Aquifer or the Anchorage artesian (Barnwell et al. 1971). Groundwater occurrence and movement took place within glacial sands and gravels deposited during Pleistocene time. The Anchorage Aquifer is a combination of an upper, unconfined zone and a lower confined zone. The upper or unconfined aquifer occurs in glacial sands and gravels which often are not areally extensive but are found as large local deposits. The lower aquifer is a confined artesian aquifer and is generally confined by lacustrine silt and clays. The areal extent of the Anchorage Aquifer is not easily determined, because the lithology of glacial deposits changes rapidly. However, the higher yielding area of the glacial deposits covers an area of approximately 200 square miles.

TANANA BASIN

Another ground-water system, which has been developed to some extent, exists in the Tanana River basin near the city of Fairbanks. The water-bearing strata of this area consist primarily of alluvial gravels, sands with minor amounts of silt comprising the river basin and alluvial fans (Anderson 1970). The areal extent of this hydrogeologic environment is quite large and may possibly cover 14,000 square miles. However, the water-bearing strata and ground-water system may not be continuous throughout this area. In the upper Tanana River basin the occurrence and movement of groundwater is severely restricted due to the presence of permafrost.

MAJOR AQUIFER WITH A.T.E.S. POTENTIAL IN REGION 12

FIGURE 12-2

YUKON-KUSKOKWIM DELTA

The Yukon-Kuskokwim River deltas, a part of the coastal lowlands in western Alaska, may also be a major aquifer. The water-yielding strata in this large river delta consist primarily of silt, sand, and thin beds of gravel. The major subsurface data have been obtained from exploratory oil wells near Bethel (Zenone and Anderson 1978). In the upper part of the deposits of the Yukon-Kuskokwim delta permafrost is widespread and to some extent limits the available ground-water storage. Near Bethel the thickness of permafrost is approximately 600 feet. Although lithologic data is available, very little hydrogeologic information is given in the literature.

BROOKS RANGE

The carbonate rocks of the Brooks Range may prove to be a potential ground-water resource. Data on this ground-water system has been inferred from the observations and measurements of springs issuing from these carbonate rocks. As is common to carbonate aquifers, the ground-water movement in these rocks has developed solution cavities and conduits through which the water flows to the surface creating the many springs (Piper 1966).

AQUIFERS UNSUITABLE FOR ATES

All of the major aquifers of Region 12 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 12-3 provides a listing of the major aquifers in Region 12 considered at this time to be unsuitable for ATES.

RESURRECTION BAY

The aquifer underlying the city of Seward and the Resurrection Bay area is considered at this time to be unsuitable for ATES development. The aquifer's low potential is primarily owing to the highly variable lithology of the river deposits and alluvial fans.

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; in other areas, unconfined.

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 UNSUITABLE RECOMMENDATIONS	COMMENTS
Resurrection Bay	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 aquifers are suitable for A.T.E.S. at a particular location.
Tanana Bay	Rapid facies changes make the hydrologic conditions vary place to place; therefore aquifers are sub-regional in extent. Permafrost is also a limiting factor.	Site-specific studies may provide information that proves the aquifers are suitable for A.T.E.S. at a particular location.
Yukon-Kuskokwin Delta	Rapid facies changes make the hydrologic conditions vary place to place; therefore aquifers are sub-regional in extent. The remoteness of the area and permafrost also limits the aquifers stability.	Site-specific studies may provide information that proves the aquifers are suitable for A.T.E.S. at a particular location.
Brooks Range Carbonates	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 12

FIGURE 12-3

TANANA BASIN

The water-bearing strata comprising the aquifer being discussed here are predominately unconfined alluvial sands and gravels. The Tanana basin is considered unsuitable because of the facies changes. Also, the discontinuous permafrost conditions present in this area are another limiting factor. The location and thickness of permafrost varies widely and near Fairbanks it reaches a thickness of 265 feet. The presence of permafrost would adversely affect the heat recovery phase, and the irregular depths and varying location of permafrost would introduce complex boundary conditions to the ground-water flow system. The limited data available indicate that this area has little ATES potential and that more detailed data must be obtained before a complete ATES evaluation can be made.

YUKON-KUSKOKWIM DELTA

The limited hydrogeologic data for this area restricts the ATES evaluation. However, an unsuitable rating has been given primarily because of the low permeability of the silt deposits and highly variable lithology expected of large river deltas. Additionally, the remoteness of much of the area and the potential problems with heat storage in an aquifer overlain by permafrost contribute to the undesirability of ATES development.

BROOKS RANGE CARBONATES

The field observations and measurements of springs discharging from the limestone strata in the eastern and western (DeLong Mountains) Brooks Range indicate the existence of high secondary porosity (Piper

1966; and Zenone and Anderson 1978). The springs and the ground-water reservoir are most likely a part of a solution cavity ground-water system. A ground-water flow system consisting of high secondary porosity is undesirable for an ATES facility because of potentially excessive flow velocities, undetermined storage volume and the inherent problems with multi-directional heat movement. For these reasons, carbonate rocks are considered undesirable for ATES development.

AQUIFERS SUITABLE FOR ATES

Data gathered on aquifers in Region 12 indicate that there are aquifers in the region that may be suitable for ATES. The data provided in Table 12-2 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 12-4 provides a listing of the aquifers considered at this time to have potential for ATES.

ANCHORAGE

The best known ground-water system in Alaska is that serving the Anchorage area (Figure 12-2). Along the eastern side of the Cook Inlet lowland the Anchorage Aquifer underlies approximately 130 square miles (Waller 1964). Glacial sands and gravel comprise the water-bearing strata. The upper unconfined aquifer varies in thickness and covers a larger area than the lower, confined aquifer. The confining layer for the lower aquifer contains silt and fine-grained sand deposits of lacustrine origin. The permeable sand and gravel deposits vary in thickness from 30 to 100 feet and are contained within the much thicker glacial deposits of the Cook Inlet area, where deposits can exceed 500 feet in depth. The underlying units are generally bedrock, which consists of relatively impermeable siltstone and argillite.

Recharge to the Anchorage Aquifer is from stream flow loss and infiltration of precipitation. The main recharge area is estimated to be between five to nine inches per year and is a major contribution to the

AQUIFER	TYPES OF A.T.E.S. STORAGE	COMMENTS
Anchorage Area	Large system — chill or low temperature storage	The potential for breaching the confining layer eliminates the development of a high temperature storage facility.

MAJOR AQUIFERS SUITABLE FOR A.T.E.S. IN REGION 12

FIGURE 12-4

confined aquifer. Recharge from stream flow particularly along Ship Creek is estimated to have a vertical infiltration rate varying from 1.0 to 2.0 feet per day along the wetted perimeter at the stream (Barnwell et al. 1972). Artificial recharge experiments show an infiltration rate as high as six feet per day for the alluvial fan along upper Ship Creek. Discharge to the local surface water system occurs during low flows and also comes from heavy municipal use from the confined aquifer. Minor amounts of discharge are released to the surrounding saltwater bodies.

The characteristics of the Anchorage aquifer contributing most to its ATES potential are its confined condition, lithology, thickness, and yield. The aquifer is confined enough to result in artesian conditions yet the upper confining layer is easily penetrated for monitoring purposes. The aquifer also has a thickness that is much less than its areal extent, which may result in conditions favorable to ATES. The lithology of unconsolidated glacial sands and gravels may offer the right balance between isotropic/anisotropic conditions, heterogeneity and flow velocity for an economic ATES facility. The aquifer's yield is nearly 2,000 gallons per minute for the largest municipal well and can easily produce sustained yields above 500 gallons per minute in most locations.

The Anchorage area aquifer would most likely be suitable for the chill storage temperature range of ATES (0° C to 10° C). The high yields obtained from this aquifer would allow use of this aquifer for a large ATES system. Aquifer water temperatures vary little and fall between 2° C to 3° C. Use of this aquifer for a low temperature ATES facility (60° C to 95° C) perhaps would result in poor thermal recovery from the large temperature difference between the aquifer fluid and

the injected fluids. The aquifer does not have adequate confinement to be considered for the high temperature (95° C to 150° C) range of ATES development because of the potential of breaching the confining layer.

Some limitations to this aquifer's potential are uncertain areal extent and present use. The aquifer may not exhibit confined conditions throughout its areal extent, and the extent of the confined aquifer may be difficult to determine because of the variability of glacial deposits. Also, the aquifer is used heavily for domestic and municipal water supply (approximately 20 million gallons per day), which results in a widespread cone of depression surrounding the municipal well field and fluctuation of the potentiometric surface with pumping rates. This may adversely affect the hydraulic gradient with respect to ATES development. However, these conditions are peculiar to Anchorage and North Kenai and may be avoided by locating an artesian aquifer in other parts of the Cook Inlet lowland deposits.

A more thorough evaluation of the Cook Inlet and Anchorage area potential for ATES may be possible in light of the most recent digital model simulation of the Anchorage confined aquifer published in 1980 by the U. S. Geological Survey in cooperation with the municipality of Anchorage. Despite the limited data available for evaluation, the Anchorage area confined aquifer has Alaska's greatest potential for ATES.

REGION'S ATES POTENTIAL

The preceding narrative outlined Alaska's major aquifers and addressed the ATES potential of each. In general, Alaska has a low ATES potential. This is because Alaska's major aquifers consist of unconsolidated alluvial or glacial deposits that are limited in yield by their low permeabilities and limited in ATES application because of permafrost conditions. Also, the sparse data available on the ground-water systems of this state may have resulted in a less than comprehensive evaluation of all Alaska's major aquifers.

There are current investigations of the ground-water systems near Anchorage and Fairbanks. The data generated in these studies will provide additional information that may be useful in a future evaluation of Alaska's ATES potential. However, it is likely that any additional data will support the conclusions of a low ATES potential for Alaska.

Owing to the regional scope of this study, only the regional aquifers of Region 12 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 therefore not preclude site-specific investigations.

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Minneapolis, MN 55455

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Washington State University
Pullman, WA 99164

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