# RECHARGE AREAS AND GEOLOGIC CONTROLS FOR THE COURTHOUSE-SEVENMILE SPRING SYSTEM, WESTERN ARCHES NATIONAL PARK, GRAND COUNTY, UTAH

by

Hugh A. Hurlow and Charles E. Bishop

SPECIAL STUDY 108
UTAH GEOLOGICAL SURVEY
a division of
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**Cover Photo:** View southeast of Courthouse Wash downstream from its confluence with Sevenmile Canyon.



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## ABSTRACT

The Courthouse-Sevenmile spring system, located in Courthouse Wash and Sevenmile Canyon along the western boundary of Arches National Park in eastern Utah, supports the base flow of Courthouse Wash and a riparian ecologic system. In this study we characterize the hydrogeology of this spring system and delineate the recharge areas contributing to its flow. The purpose of the study is to assist the National Park Service and Utah Division of Water Rights in establishing limits on future ground-water withdrawals in the recharge area of the Courthouse-Sevenmile spring system, to maintain the present flow and water quality and to ensure the stability of the associated ecologic system. The study includes analysis of the geologic setting of the springs and their recharge areas, geochemical and physical characterization of spring water, and calculations of the recharge areas for the springs. Geochemical and flow data were collected from Courthouse Wash Boundary Spring and Sevenmile Canyon Boundary Spring, but the data represent physical conditions throughout the Courthouse-Sevenmile spring system.

Courthouse Wash and Sevenmile Canyon partition the Courthouse-Sevenmile spring system into three geographic groups with distinct recharge areas. The northern group includes Courthouse Wash Boundary Spring and two springs along the west wall of Courthouse Wash north of the confluence with Sevenmile Canyon, and derives its flow from bedrock to the northeast, north, and northwest. The eastern spring group is along the east wall of Courthouse Wash and derives its flow from bedrock east of Courthouse Wash. The western spring group, including Sevenmile Canyon Boundary Spring, is along the south wall of Sevenmile Canyon and the west wall of Courthouse Wash below the confluence with Sevenmile Canyon, and derives its flow from bedrock southwest of the confluence.

The shallow Moab Member aquifer, which consists of the Moab Member of the Jurassic Curtis Formation, is the dominant source of flow in the Courthouse-Sevenmile spring system, based on the following observations:

1. All springs and seeps in the Courthouse-Sevenmile spring system issue from the Moab Member aquifer, composed of well-sorted, calcite-cemented, densely jointed eolian sandstone. Most discharge is from the basal contact or from cross-bed-truncation surfaces within 25 feet (8 m) of the base of the Moab Member, except for Courthouse Wash Boundary Spring and one spring in the northern group, which issue from cross-bed planes near the top of the Moab Member.
2. The chemistry, temperature, pH, and dissolved-oxygen content of spring water from the eastern and western spring groups indicate that water discharging from the Courthouse-Sevenmile spring system is part of a shallow aquifer system with a relatively short (about 50 years) travel time between recharge and discharge areas, and that water chemistry is affected mainly by dissolution of calcite cement in the Moab Member. Spring-water chemistry also suggests that recharge to most of the Moab Member shallow aquifer occurs by infiltration of precipitation on Moab Member outcrops. Courthouse Wash Boundary Spring water, in contrast, has a slightly saline geochemical signature, suggesting mixing of water of the Moab Member aquifer with water that has passed through other geologic units. The most likely sources for the saline water are (1) alluvium in Courthouse Wash, derived in part from the Jurassic Morrison Formation and the Cretaceous Cedar Mountain Formation

and Mancos Shale, exposed upstream from the spring, and (2) water that has percolated through the Morrison and/or Summerville Formations into the Moab Member aquifer where it underlies these formations west and north of Courthouse Wash Boundary Spring.

3. Geologic boundary conditions partly control ground-water flow to the springs. Ground-water flow follows the regional dip directions of the limbs of the Courthouse syncline, whose axis approximately coincides with Courthouse Wash. The Moab fault severs the Moab Member aquifer on the southwest, and forms an impermeable barrier to horizontal ground-water flow from the southwest into the study area. The eroded southwestern limb of the Salt Valley anticline forms the northeastern boundary of the Moab Member aquifer. The Jurassic Summerville and Morrison Formations form a low-permeability layer above the Moab Member, impeding major recharge to the Moab Member aquifer by infiltration of precipitation where they overlie it. The contact between the Moab Member and the underlying Slick Rock Member of the Entrada Sandstone is lined with fine-grained, impermeable deposits that precipitated from ground water. These deposits likely prevent percolation of ground water from the Moab Member downward into the Slick Rock Member.

We used water-budget and catchment-area methods to estimate the land-surface area needed for recharge of the part of the Moab Member aquifer that contributes to discharge at Courthouse Wash Boundary Spring, Sevenmile Canyon Boundary Spring, Poison Ivy Spring, and Sleepy Hollow Spring, and a volumetric travel-time method to estimate the aquifer area contributing to these springs. The water-budget method yields recharge-area estimates of about 1.05 square miles (2.7 $km^2$) for Courthouse Wash Boundary Spring, 0.67 square mile (1.7 $km^2$) for Sevenmile Canyon Boundary Spring, 0.35 square mile (0.9 $km^2$) for Poison Ivy Spring, and 0.64 square mile (1.7 $km^2$) for Sleepy Hollow Spring. The catchment-area method yielded similar results. Aquifer areas estimated using the travel-time method are about 25 percent of the areas estimated from the water-budget and catchment-area methods.

Based on the ratios of estimated recharge area to discharge for the springs and on estimated flows from unmeasured springs and seeps, the eastern spring group requires about 2.04 square miles (5.3 $km^2$) of recharge area to support its discharge, and the western spring group requires about 1.5 square miles (3.9 $km^2$) of recharge area to support its discharge.

Courthouse Wash Boundary Spring and the rest of the northern spring group are directly connected to the confined Moab Member aquifer which underlies private and state-owned land west to northwest of the Arches National Park boundary. Ground-water levels and the base of the Moab Member aquifer below this land both slope toward Courthouse Wash, suggesting a component of ground-water flow in that direction. Recharge from the confined Moab Member aquifer in this area, therefore, contributes to the discharge of Courthouse Wash Boundary Spring. Insufficient data exist to estimate the proportion of Courthouse Wash Boundary Spring's discharge supplied by the confined part of the Moab Member aquifer. Future increases in ground-water withdrawal from the Moab Member aquifer below these lands could strongly impact the flow of Courthouse Wash Boundary Spring.

The western spring group receives recharge from the unconfined part of the Moab Member aquifer southwest of Courthouse Wash and Sevenmile Canyon. Our calculations indicate that the land-surface area required to support the discharge of the western spring group is comparable to the outcrop area of the Moab Member upgradient of the springs. The western spring group is, therefore, highly vulnerable to contamination and withdrawal of ground water from the Moab Member aquifer southwest of Courthouse Wash and Sevenmile Canyon. Existing water wells nearby are screened in the Cutler Formation in the footwall of the Moab fault, whereas the source area for the western spring group is in the hanging wall of the fault. Because the Moab fault is considered a ground-water barrier, these wells do not likely affect ground-water flow to the western spring group.

## INTRODUCTION

Courthouse Wash is the only perennial, or nearly perennial, stream in the southwestern part of Arches National Park, and supports a stable riparian environment that is critical to the ecology of the park and adjacent areas (figure 1). Springs and seeps along the canyon walls of Courthouse Wash and lower Sevenmile Canyon in and adjacent to the western part of Arches National Park, herein referred to as the Courthouse-Sevenmile spring system, provide the base flow for Courthouse Wash (figures 2, 3, and 4). Due to relatively small flows and its location in a desert environment, the Courthouse Wash ecohydrologic system is highly vulnerable to long-term changes in volume and quality of recharge. Current and future ground-water development on private and state-owned land adjacent to the western park boundary (figure 3) may, therefore, adversely affect the quantity and quality of water issuing from the springs and seeps feeding Courthouse Wash, and relatively small long-term changes in spring flow could strongly impact this ecologic system.

This study, performed at the request of and in cooperation with the National Park Service, characterizes the geologic controls and delineates the recharge areas for the Courthouse-Sevenmile spring system. Our work focuses on two of the major springs feeding Courthouse Wash, informally referred to by the National Park Service as Courthouse Wash Boundary Spring and Sevenmile Canyon Boundary Spring (figures 2 and 3; plate 1). Data from this report will be used by the National Park Service and the Utah Division of Water Rights to establish limits on future ground-water appropriations west and northwest of the park, to preserve the present environmental quality and ecologic stability of Courthouse Wash.

The National Park Service chose to focus on Courthouse Wash and Sevenmile Canyon Boundary Springs for this study because they appeared representative of the larger Courthouse-Sevenmile spring system and vulnerable to addi-

A

B


***Figure 1.*** *Views of Courthouse Wash. A. View downstream (southeast). B. View upstream (northwest) of confluence area of lower Sevenmile Canyon and Courthouse Wash.*

A


B


***Figure 2.*** *Views of the springs focused on in this study. A. Courthouse Wash Boundary Spring. Dark areas on bedrock just above wash (left front of photo) show ground water issuing from joints in the upper part of the Moab Member of the Curtis Formation (Jctm). Qao is older alluvium. B. Sevenmile Canyon Boundary Spring. The spring in shadows, issues from the contact between the Moab Member of the Curtis Formation (Jctm) and the Slick Rock Member of the Entrada Sandstone (Jes).*

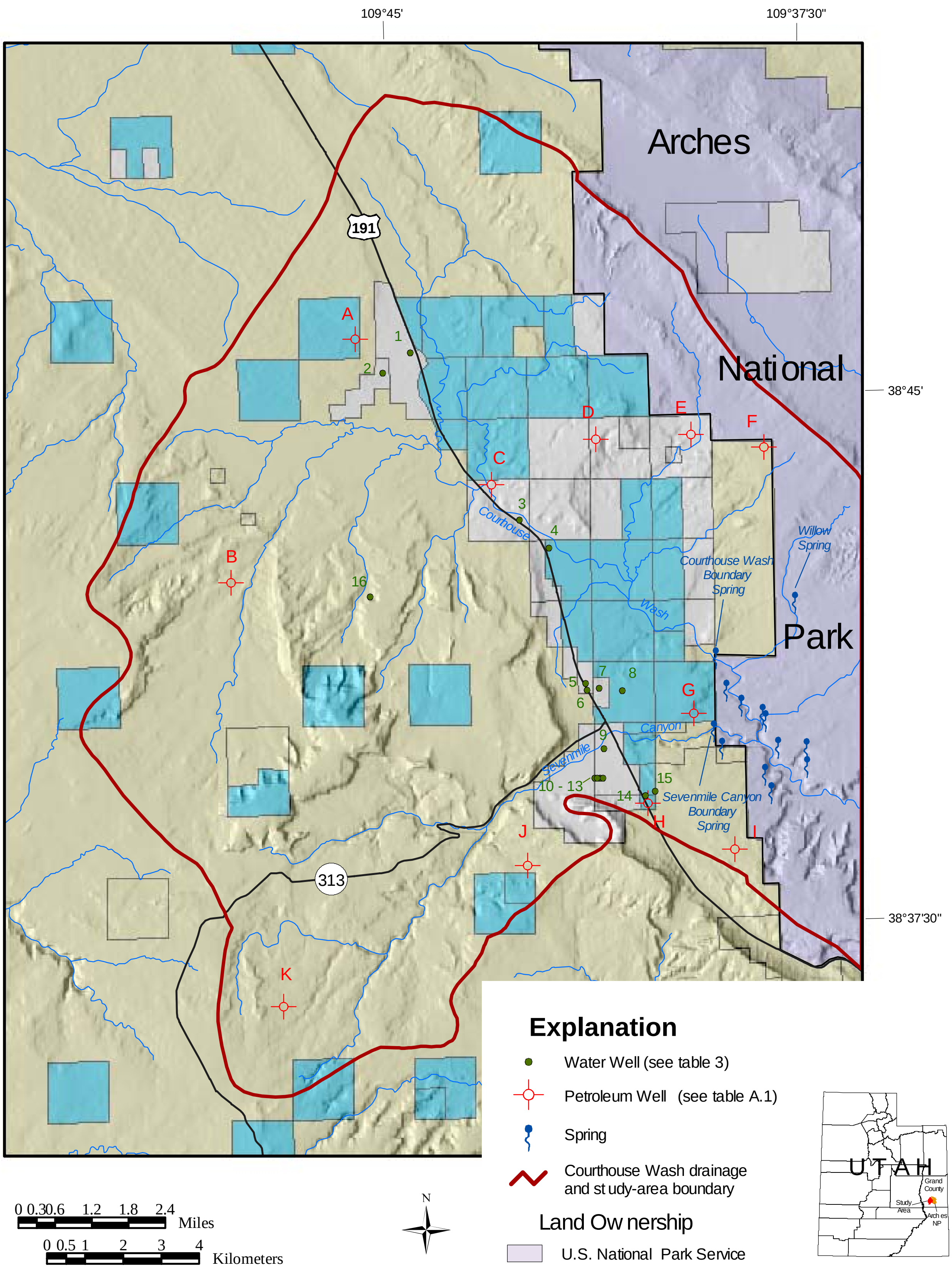



***Figure 3.*** *Physiographic and hydrologic features of the study area.*

tional future ground-water withdrawal by wells, and due to the feasibility of measuring their discharge compared to other springs in the system.

The Sevenmile Canyon and Courthouse Wash surface drainage consists of about 162 square miles (420 km²) in the Upper Colorado River Basin. The surface drainage encompasses the Courthouse-Sevenmile spring system, a small commercial development, and undeveloped rural land. The study area for this report encompasses the Courthouse Wash and Sevenmile Canyon surface-drainage areas west of Arches National Park, and the major springs and seeps of the Courthouse-Sevenmile spring system in the western part of the park (figures 3 and 4). The "Courthouse Wash-lower Sevenmile Canyon area" as used in this report includes about 30 square miles (78 km²) surrounding the Courthouse-Sevenmile spring system (plate 1).

Our approach to delineating the recharge area for the Courthouse-Sevenmile spring system included (1) determining the geologic controls on ground-water flow and spring location, (2) developing a conceptual model for the ground-water flow system contributing to spring discharge, and (3) estimating recharge areas for groups of springs and seeps having common source areas. Geologic work included field examination of springs and seeps and major structures to determine the influence of stratigraphy and structure on spring location, and quantitative and qualitative description of joints and faults that may influence ground-water flow. We developed a conceptual model for ground-water flow and spring discharge by considering a wide variety of data, including spring discharge records, field parameters and chemistry of spring water, water levels in wells, precipitation, hydrostratigraphy, and the hydrogeologic properties of structures. We collected new field-parameter and water-chemistry data for Courthouse Wash Boundary Spring and Sevenmile Canyon Boundary Spring, and also considered previous discharge and chemical data. We estimated land-surface and aquifer areas contributing to spring flow using simple equations, and tailored the shapes and locations of the estimated recharge areas to geologic and topographic boundary conditions and to our conceptual model for ground-water flow.

The principal conclusions of this report are as follows:

(1) Springs in the study area form three geographic groups with distinct recharge areas: the northern group, including Courthouse Wash Boundary Spring, along the west side of Courthouse Wash north of its confluence with lower Sevenmile Canyon; the western group, including Sevenmile Canyon Boundary Spring, along the south side of lower Sevenmile Canyon and the western side of Courthouse Wash below its confluence with lower Sevenmile Canyon; and the eastern group, along the east side of Courthouse Wash (plate 1).

(2) Geochemical, temperature, and dissolved-oxygen data indicate that the ground-water flow system supplying the Courthouse-Sevenmile spring system is contained entirely in the Moab Member aquifer, except for Courthouse Wash Boundary Spring, which receives some recharge from alluvium in Courthouse Wash and/or the Morrison and Summerville Formations overlying the Moab Member. The residence time of ground water in the Moab Member aquifer is relatively short, although we lack sufficient data to provide a precise estimate.

(3) Ground water enters the Moab Member aquifer primarily by infiltration of precipitation on outcrops, flows within the Moab Member aquifer down the dip of both limbs of the Courthouse syncline, and discharges in the hinge zone, which is spatially coincident with Courthouse Wash. The area of recharge for the Moab Member aquifer lies entirely within the surface-drainage area for Courthouse Wash and Sevenmile Canyon. North and west of the Courthouse-Sevenmile spring system, the Moab Member aquifer is confined below the Summerville and Morrison Formations. Recharge to the confined Moab Member aquifer may occur by infiltration of precipitation through the Summerville and Morrison Formations, or by southward flow within the Moab Member along the Moab fault.

(4) Most springs in the study area issue from the contact between the Moab Member of the Curtis Formation and the underlying Slick Rock Member of the Entrada Sandstone, and from cross-bed-truncation planes within the lower 25 feet (8 m) of the Moab Member. Courthouse Wash Boundary Spring and another, unnamed spring in the northern spring group issue from the top of the Moab Member.

(5) We estimated contributing areas for spring flow in the Courthouse-Sevenmile spring system using water-budget, catchment-area, and travel-time methods. The three methods yield reasonable, internally consistent results compatible with our understanding of the hydrogeologic setting and boundary conditions of the Courthouse-Sevenmile spring system.

(6) Courthouse Wash Boundary Spring is directly connected to the confined part of the Moab Member aquifer underlying private and state-owned land to the west and northwest. The western spring group is connected to the unconfined part of the Moab Member aquifer underlying public lands southwest of Sevenmile Canyon and Courthouse Wash, and the eastern spring group is connected to the unconfined part of the Moab Member aquifer underlying Arches National Park east of Courthouse Wash. All of these springs are vulnerable to future increased ground-water withdrawals or contamination in their recharge areas.

Many geologic terms used in the text are defined in the glossary at the end of this report.

# GEOLOGIC SETTING

## Regional

The study area is in the Colorado Plateau physiographic province of eastern Utah (Stokes, 1977), characterized by exposures of late Paleozoic- and Mesozoic-age (see figure A.1 for geologic time scale) sedimentary rocks mantled by thin surficial deposits and cut by streams and washes that in many places form steep-sided canyons. Bedding throughout the Colorado Plateau dips gently except near relatively widely spaced folds and faults. The Colorado River is the major stream draining the study area and southeastern Utah (figure 4); its development has controlled base level, and thus local topography and ground-water flow in the region.

Tectonically, Arches National Park and the study area are in the salt anticline region of the Paradox depositional basin of Pennsylvanian to Permian age (figure 5). The Paradox basin formed as the land surface subsided due to loading of the earth's crust by the hanging wall of the Uncompahgre fault, a northwest-striking reverse fault bounding the northeastern basin margin (figure 5) (Elston and others, 1962; Cater, 1970; Doelling, 1988). The Paradox basin accumulated up to about 10,000 feet (3,050 m) of sediment, including salt, anhydrite, and shale of the Pennsylvanian Paradox Formation; limestone, siltstone, and sandstone of the Pennsylvanian Honaker Trail Formation; and arkosic sandstone and conglomerate of the Permian Cutler Formation (figure 6) (Doelling, 1988, 2001).

Beginning soon after initial deposition of the Paradox Formation and ending in Cretaceous time, buried salt rose as diapirs through overlying sediments (Elston and others, 1962; Cater, 1970; Doelling, 1988). Diapiric movement was most rapid during Permian through Triassic time, and was minimal and localized during Jurassic time. These elongate, northwest-trending diapirs formed the "salt anticlines" of the Paradox basin (figure 5) (Cater, 1970; Doelling, 1988). Intervening synclines formed due to the combined effects of uplift of strata above the salt anticlines and flow of underlying salt toward the rising diapirs. The linear form and parallel alignment of these diapirs resulted from localization by pre-existing, northwest-striking faults (Cater, 1970; Doelling, 1988). Pennsylvanian through Triassic stratigraphic units thin rapidly and exhibit facies changes toward the salt anticlines, and contain intraformational and interformational angular unconformities due to deposition during ongoing diapirism (Cater, 1970; Doelling, 1988; Hazel, 1994).

Late Cenozoic uplift of the Colorado Plateau led to development of the Colorado River drainage system, accompanied by fluvial erosion that removed thousands of feet of sedimentary rock from the region. Downcutting during Pleistocene time was accompanied by the formation of rock benches and a system of cliff-walled canyons that have been cut into the higher rock benches along major streams and many smaller tributaries. These landforms affect the areal distribution of ground-water recharge, discharge, and movement (Freethey and Cordy, 1991). During Quaternary time, ground-water circulation caused dissolution and removal of Paradox Formation salt in the cores of several salt anticlines, producing the breached-anticline morphology characteristic of the salt anticline region (Cater, 1970; Doelling, 1988).

Holocene sedimentation is characterized by alternating cycles of alluvial deposition and erosion, with little additional downcutting. Eolian deposits locally cap the canyon rims and benches within the canyons.

## Study Area

Upper Cretaceous through Pennsylvanian bedrock units crop out in the study area (figure 7). Quaternary alluvial and eolian deposits form thin veneers on bedrock and are up to 50 feet (15 m) thick in washes (Doelling and Morgan, 2000; Doelling, 2001). Exposed in the hanging wall of the Moab fault are: (1) arkosic sandstone of the Permian Cutler Formation, (2) interbedded sandstone and mudstone of the Triassic Chinle and Moenkopi Formations, and (3) sandstone of the Wingate Sandstone, the Kayenta Formation, and the Navajo Sandstone, all Jurassic in age (figures 6 and 8A; plate 1). Jurassic rocks crop out in the Courthouse Wash-lower Sevenmile Canyon area (plate 1), including siltstone, sandstone, and minor limestone and chert of the Morrison and Summerville Formations (figure 8B); eolian sandstone of the Moab Member of the Curtis Formation (figure 8C); eolian and shallow-water sandstone of the Slick Rock Member of the Entrada Sandstone (figures 8C and 8D); and siltstone and fine-grained sandstone of the Dewey Bridge Member of the Carmel Formation (figure 8D) (Doelling and Morgan, 2000; Doelling, 2001). The Moab and Dewey Bridge Members were formerly included in the Entrada Sandstone, but recent stratigraphic work shows that the contacts between these units and the Slick Rock Member correlate with previously established regional unconformities, requiring their assignment to different formations (Doelling, 2001).

The Courthouse syncline, the Salt Valley anticline, and the Moab fault dominate the structure of the study area (figure 7; plate 1). The broad, open Courthouse syncline originally formed due to salt withdrawal during formation of the Salt Valley anticline, and was amplified during the early Tertiary Laramide orogeny (Doelling, 1988). Strata on the limbs of the Courthouse syncline in the study area strike northwest and dip 1° to 5° toward the hinge zone (figure 7; plate 1; cross sections B-B′ through E-E′, plate 2).

The northwest-striking Moab fault displaces the southwestern limb of the Moab-Spanish Valley salt anticline down to the northeast with a maximum throw of about 2,600 to 3,100 feet (790-945 m) (figures 7 and 9; cross sections B-B′ and D-D′, plate 2) (Doelling, 1988, 2001; Foxford and others, 1996; Olig and others, 1996). Doelling (1988, 2001) and Olig and others (1996) interpret the Moab fault as a primarily Tertiary structure, but Foxford and others (1996) present stratigraphic evidence suggesting that it was also active during formation of the salt anticlines in Triassic time.

# HYDROLOGIC SETTING

## Geography and Climate

The study area is in and adjacent to the western part of Arches National Park in south-central Grand County, about 10 miles (16 km) northwest of Moab (figures 3 and 4). The surface elevation in the study area ranges from about 4,300 to 5,890 feet (1,310-1,795 m), and the land surface forms a broad plateau capped by small, gently sloped hills and cut by

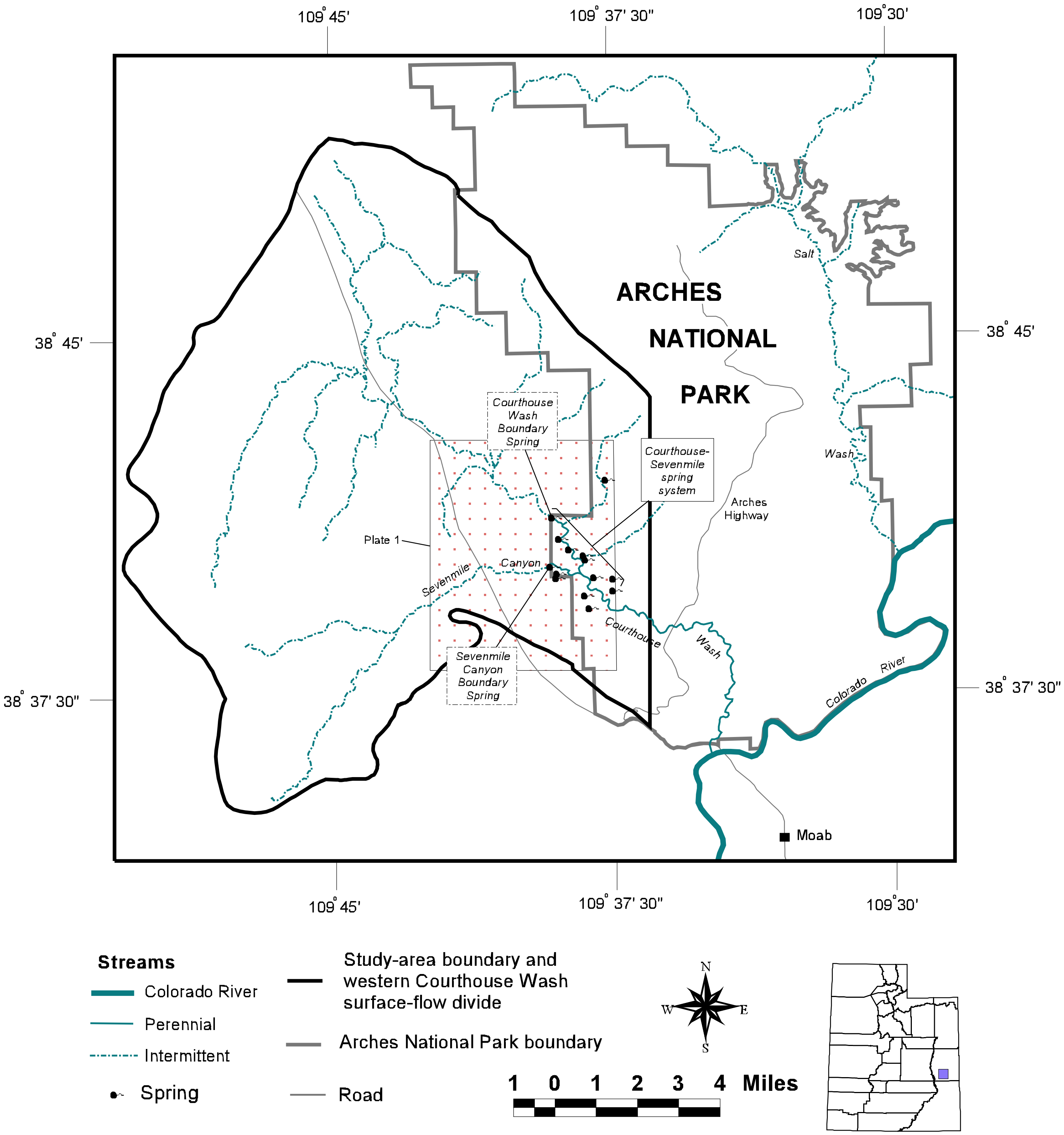



*Figure 4. Regional geographic and hydrologic setting of the study area.*

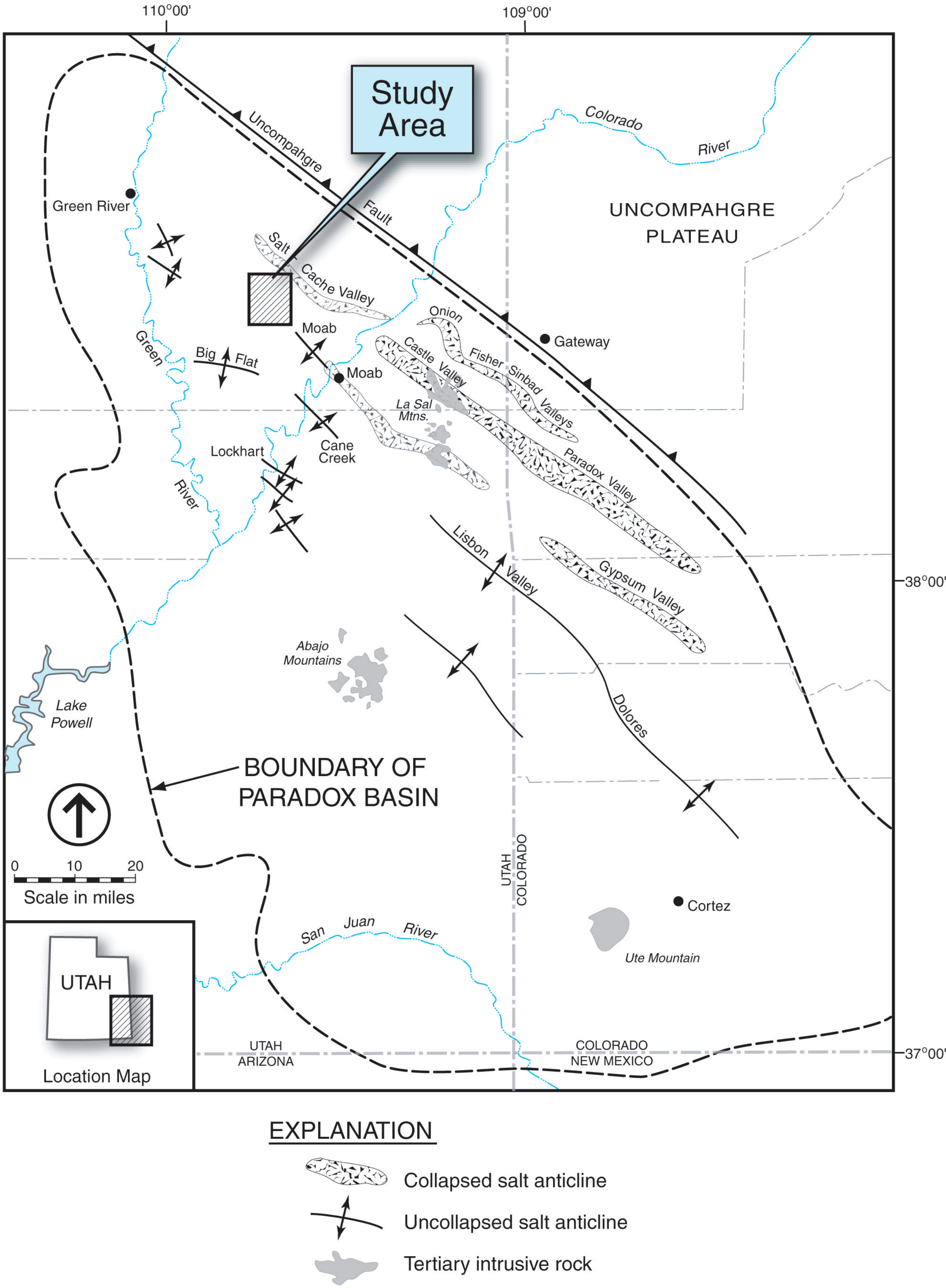



*Figure 5. Regional tectonic setting of the study area, showing major features including salt anticlines, Paradox basin, Uncompahgre Plateau and fault, and Tertiary intrusions (modified from Doelling, 1988).*

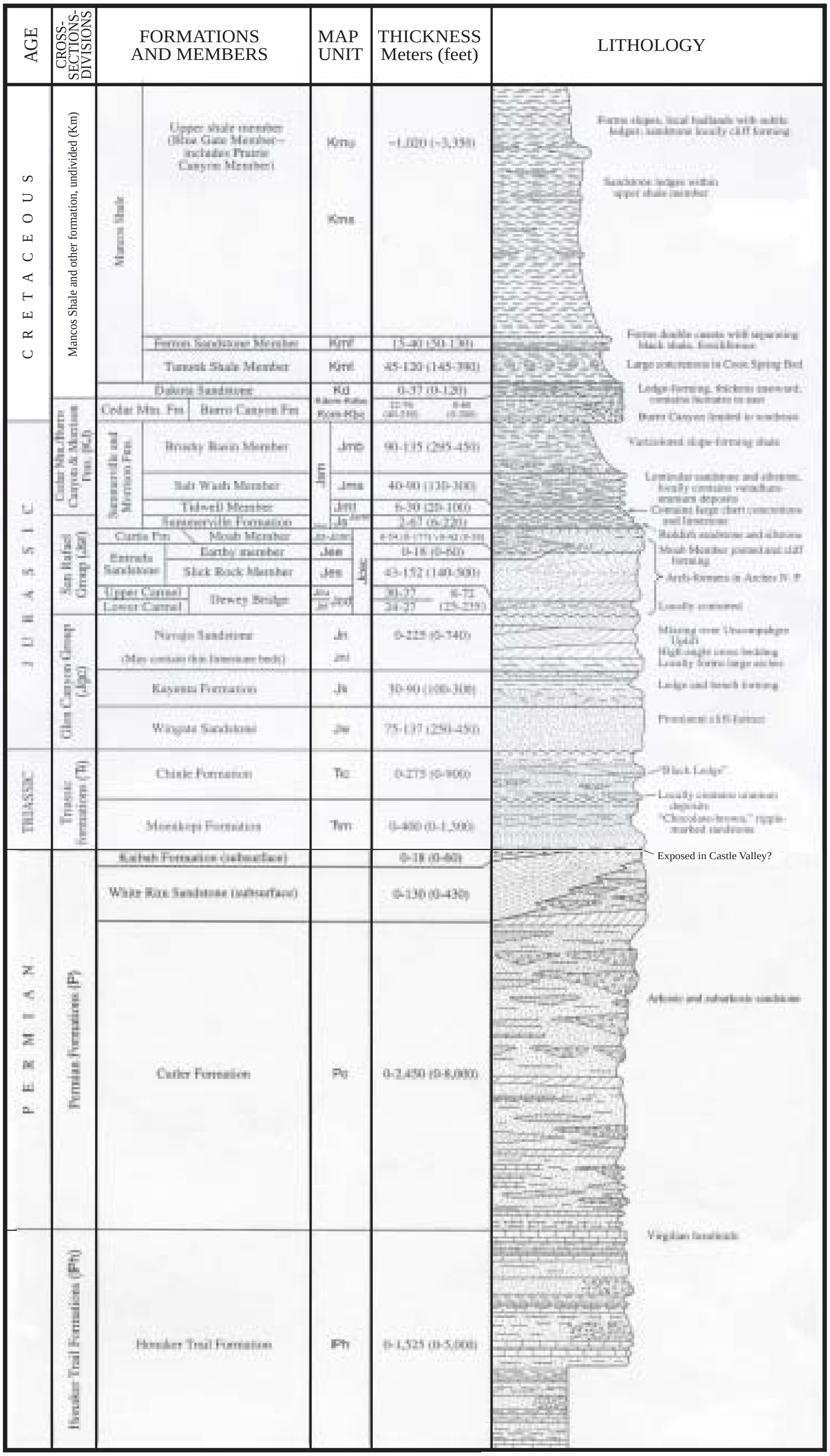



***Figure 6.*** *Stratigraphic column for the study area (Doelling, 2001). Not all units shown in this stratigraphic column are present on figure 7.*

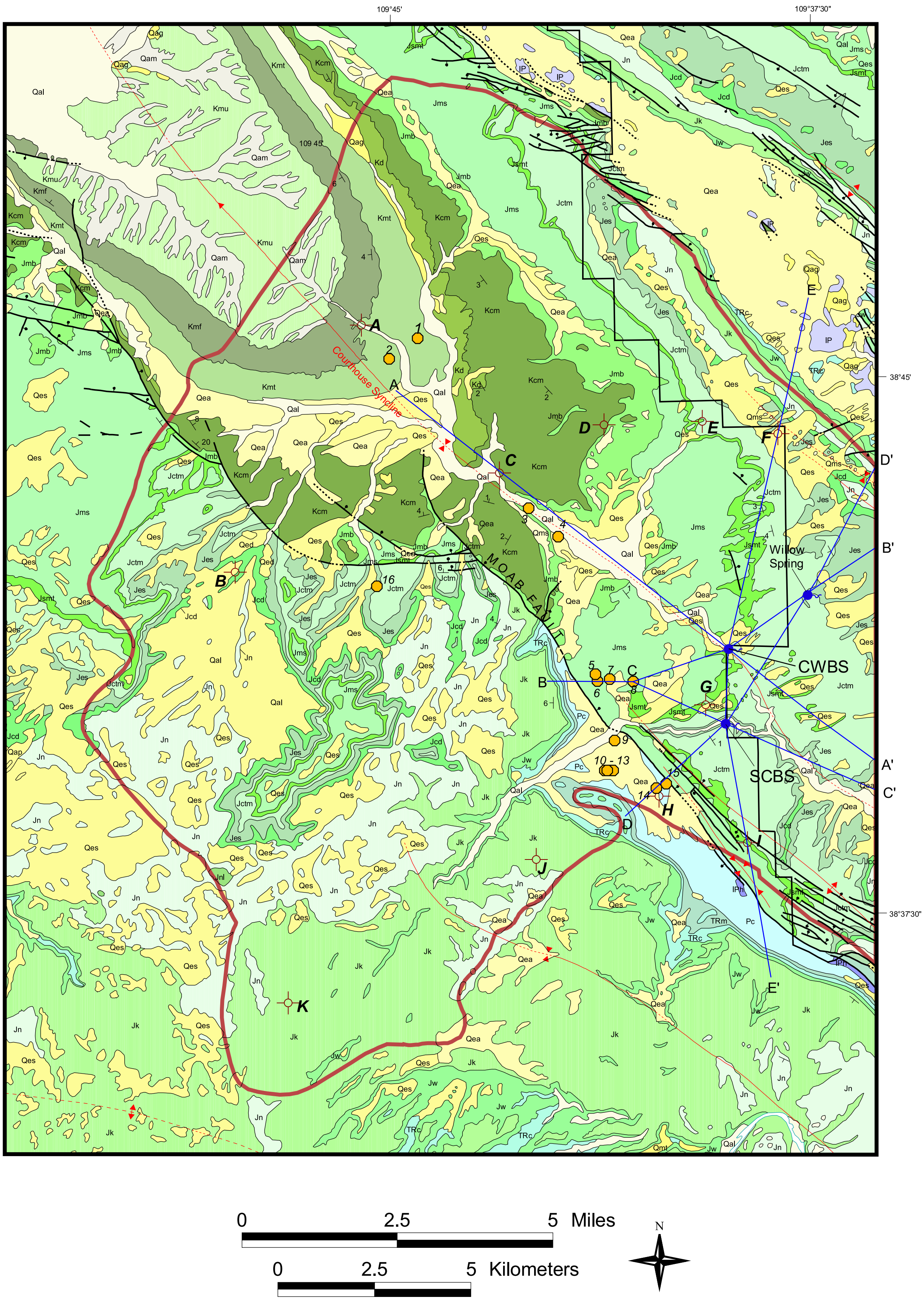



***Figure 7.*** *Generalized geologic map of the study area (Doelling, 2001).*

**Figure 7.** *(conitnued)*

## EXPLANATION

Map Units - see appendix A for descriptions.

Quaternary
- Qal - Stream alluvium
- Qag - Alluvial gravel
- Qea - Mixed eolian and alluvial deposits
- Qes - Eolian deposits

Cretaceous
- Kmu - Upper Shale Member of Mancos Shale
- Kmf - Ferron Sandstone Member of Mancos Shale
- Kmt - Tununk Shale Member of Mancos Shale
- Kd - Dakota Sandstone
- Kcm - Cedar Mountain Formation

Jurassic
- Jmb - Brushy Basin Member of Morrison Formation
- Jms - Salt Wash Member of Morrison Formation
- Jsmt - Tidwell Member of Morrison Formation and Summerville Formation, undivided
- Jctm - Moab Member of Curtis Formation
- Jes - Slick Rock Member of Entrada Sandstone
- Jcd - Dewey Bridge Member of Carmel Formation
- Jn - Navajo Sandstone
- Jk - Kayenta Formation
- Jw - Wingate Sandstone

Triassic
- ŦRc - Chinle Formation
- ŦRm - Moenkopi Formation

Permian
- Pc - Cutler Formation

Pennsylvanian
- IPh - Honaker Trail Formation

## SYMBOLS

- Contact - dashed where location inferred
- Fault - dashed where location inferred, dotted where concealed; ball and bar on downthrown side
- Anticline - dashed where location inferred; arrow shows direction of plunge
- Syncline - dashed where location inferred; arrow shows direction of plunge
- 5 Strike and dip of bedding
- 3 Water well - see table 3
- Spring - see table 4
- Petroleum exploration well - plugged and abandoned; see table A.1
- B-B' Cross section - see plate 2
- Arches National Park boundary
- Study area boundary

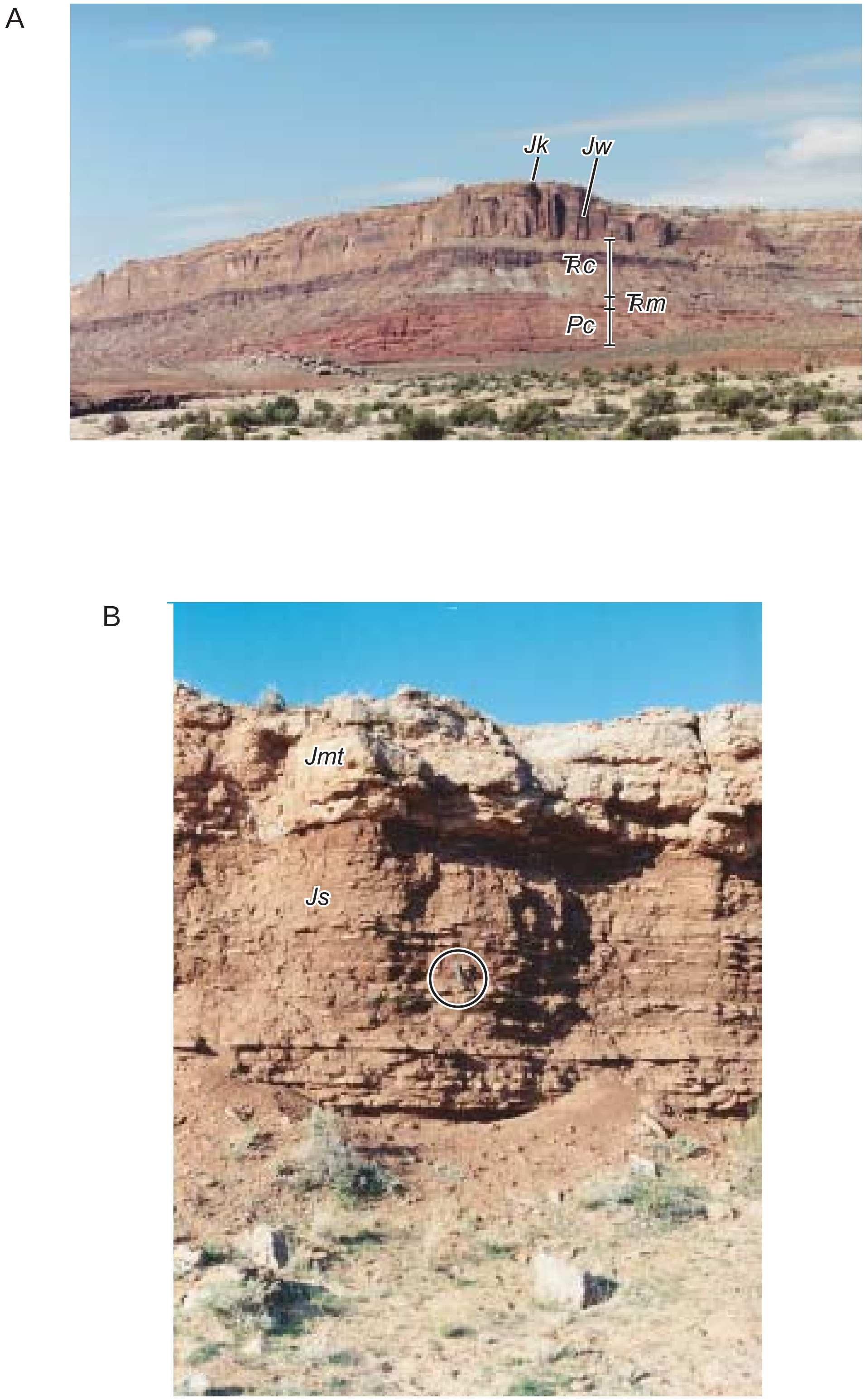
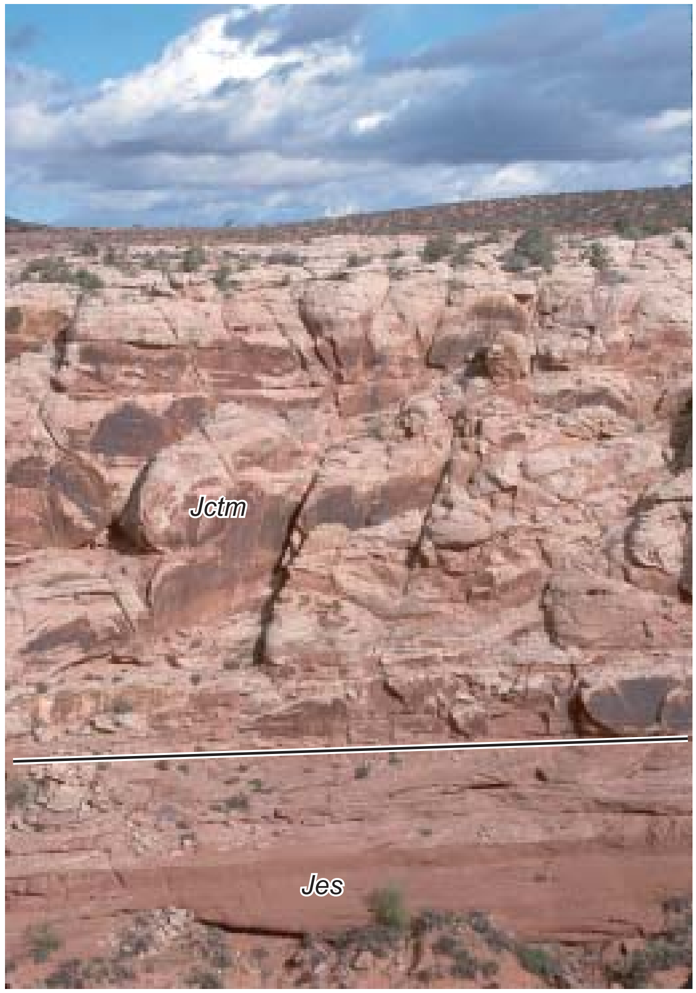



***Figure 8***. *Prominent geologic units and structures in the study area. See figure 6 and appendix A for information on rock units. A. View west to cliff on north side of upper Sevenmile Canyon, west of U.S. Highway 191. Cliff is about 800 feet (244 m) high. Jk – Kayenta Formation; Jw – Wingate Sandstone; TRc – Chinle Formation; TRm – Moenkopi Formation; Pc – Cutler Formation. B. Outcrops of Summervile Formation (Js) and Tidwell Member of the Morrison Formation (Jmt) (combined as unit Jsmt on figures 6 and 7 and plate 1), about 100 feet (30 m) southwest of Courthouse Wash Boundary Spring. These units overlie, and form a confining layer above, the Moab Member of the Curtis Formation (not shown). Hammer (circled) is 11 inches (23 cm) long.*

C




D


***Figure 8 (continued).*** *C. Moab Member of Curtis Formation (Jctm) above Slick Rock Member of Entrada Formation (Jes) on north wall of lower Sevenmile Canyon near canyon head. Contact shown by black line. The Moab Member is about 80 feet (24 m) thick here and has much greater joint density than the Slick Rock Member. D. Slick Rock Member of the Entrada Sandstone (Jes) overlying Dewey Bridge Member of the C armel Formation (Jcd) in Arches National Park, about 0.25 mile (0.4 km) west of the Arches Highway bridge over Courthouse W ash. Cliff is about 300 feet (91 m) high.*

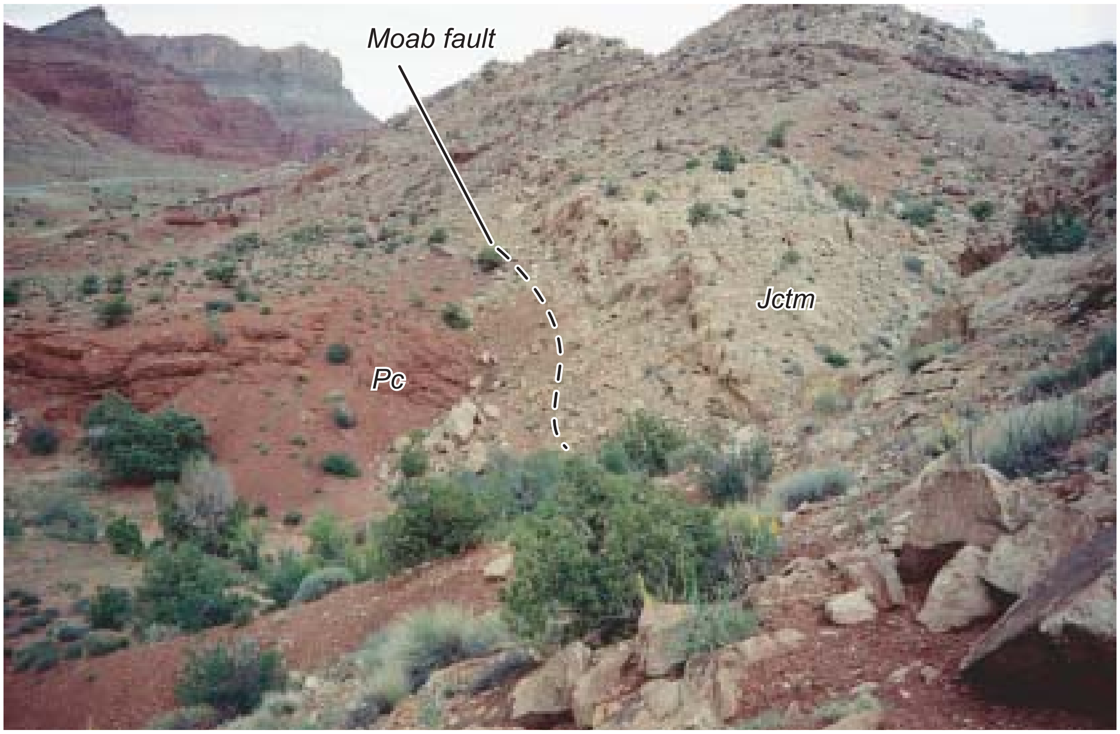



***Figure 9.*** *View northwest of the Moab fault (dashed line), about 2 miles (3.2 km) southeast of the southern study-ar ea boundary. The Moab fault juxtaposes densely jointed Moab Member of the Curtis Formation (Jctm) in its hanging wall against Cutler Formation (Pc) in its footwall. Note the normal-drag fold in the Cutler Formation adjacent to the fault. The dense jointing in the Moab Member likely enhances fault-pa rallel ground-water flow in the subsurface.*

narrow, steep canyons (figure 3; plate 1). In the Courthouse-Sevenmile Canyon area, the plateau is developed on the upper surface of the Moab Member of the Curtis Formation, and the capping hills are composed of overlying, less resistant Jurassic and Cretaceous rocks. The steep-sided canyons are cut into and through the Moab Member of the Curtis Formation and into the Slick Rock Member of the Entrada Sandstone (plate 1).

Altitude and topography influence the movement of air masses and storms, causing temperature and precipitation to vary widely in the region (Freethey and Cordy, 1991). Table 1 presents a summary of average annual temperatures and precipitation at weather stations in and near the study area, and figure 10 shows the areal distribution of precipitation. The weather-station data indicate a dry period from November through June, and a wetter period from July through October. Warm, moisture-laden air masses from the Gulf of Mexico traverse the region in summer, and Pacific air masses and storms dominate the regional weather during October through April (Blanchard, 1990). Because most moisture-bearing air masses come from the south and southeast, the study area is in a rain shadow on the leeward side of the La Sal Mountains (Blanchard, 1990). Based on data from the National Weather Service (2002), average annual precipitation on the mesas and broad outcrop areas ranges from less than 6 inches (15 cm) to a little more than 10 inches (25 cm) and is about 9 inches (23 cm) in the study area (figure 10).

Summer precipitation is sporadic and convectional in nature. Infrequent thunderstorms produce local, high-intensity rainfall that causes heavy runoff and may result in flash floods. The storms are distributed randomly in areas of low relief, but are concentrated on and along highlands and result in limited ground-water recharge because they are of short duration, lasting only a few hours. More precipitation falls during the summer than in the winter.

Winter and spring precipitation is chiefly frontal, due to Pacific air masses bringing sustained precipitation to the area. The frontal storms produce either rain or snow; small quantities of snow accumulate on the ground for a short while. During fall, winter, and early spring, temperatures are cool, and evapotranspiration is minimal. Precipitation is more evenly distributed, and intensity is generally low allowing for greater ground-water recharge.

Seasonal temperature ranges are wide; temperature extremes at Arches National Park Headquarters are over 100°F (37.8°C) and below 0°F (-18°C) (National Weather Service, 2002). During the summer and fall seasons (July to October) the maximum daily temperature averages about 88°F (56°C), and during the winter season (November to February) the maximum daily temperature is about 49°F (9°C) and can drop below freezing (National Weather Service, 2002). Mean annual temperature is a function of location and altitude, with cooler temperatures found at higher altitudes. Potential evapotranspiration in the study area ranges from 42 to 52 inches (107-132 cm) per year, greatly exceeding annual precipitation (Ashcroft and others, 1992).

## Surface Water

Arches National Park and the study area are drained by the Colorado River, whose deep canyon borders the park on the southeast (figure 4). Drainages in the area are generally ephemeral and dry, with surface flow caused by extreme but infrequent summer and early fall thundershowers. Perennial reaches of streams are maintained by ground-water discharge

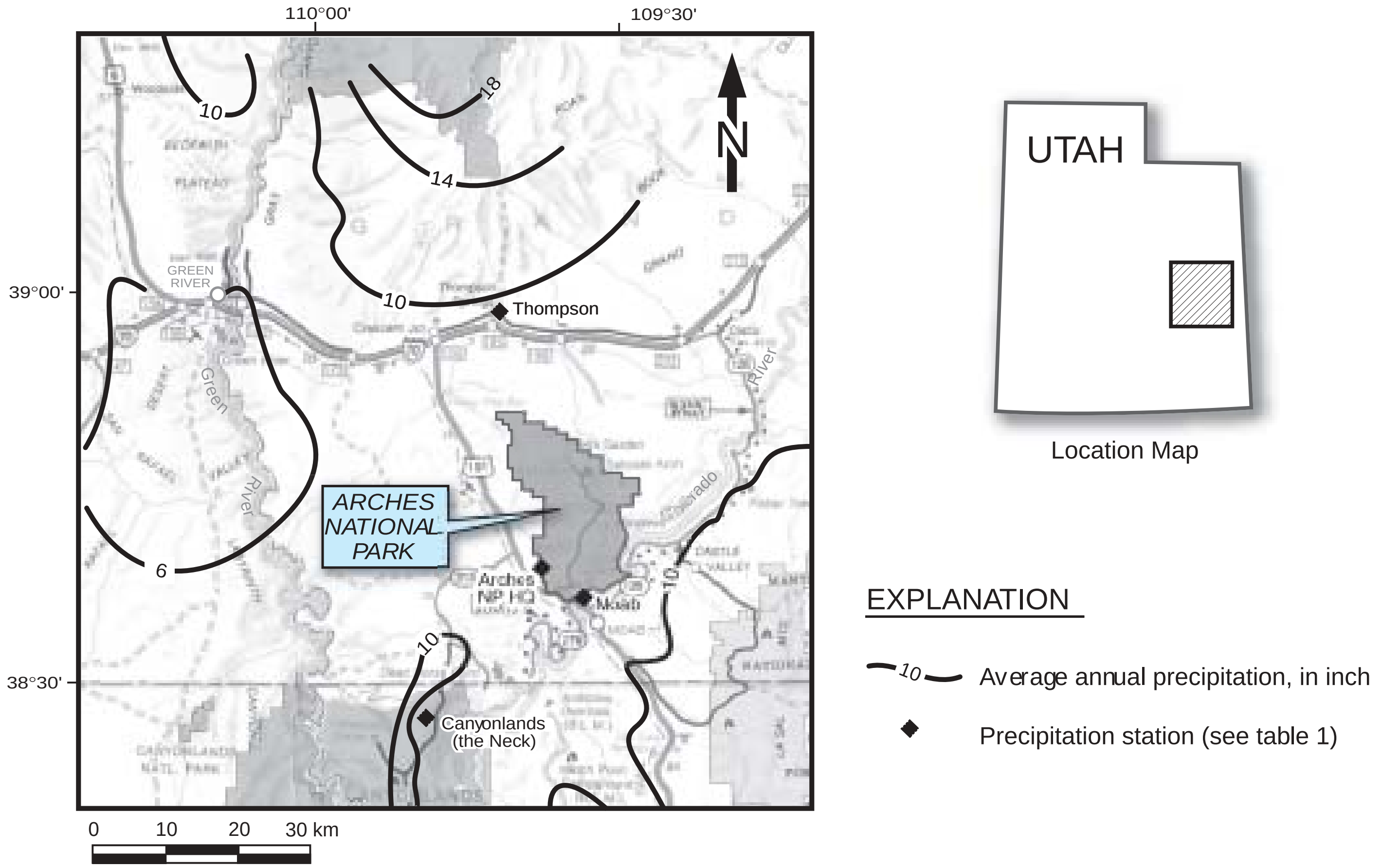



***Figure 10.*** *Areal distribution of average annual precipitation and location of precipitation gauges (lines of equal precipitation modified from Woodward-Clyde Consultants, 1982).*

and are mostly adjacent to springs. Flows are generally confined to channels, although they frequently inundate the flood plains during extreme thundershowers, where the channels are not deeply incised.

Sevenmile Canyon and Courthouse Wash make up the surface watershed in the study area. The surface drainage area of Sevenmile Canyon to its confluence with Courthouse Wash is about 31 square miles (80 $km^2$). Courthouse Wash above the confluence with the Colorado River, not including Sevenmile Canyon, drains about 131 square miles (339 $km^2$). Sevenmile Canyon has two distinct segments, located approximately east and west of U.S. Highway 191 (figure 3); in this report we informally refer to the segment east of the highway as lower Sevenmile Canyon. Lower Sevenmile Canyon is steep-sided, narrow, and flat-bottomed along its entire length. Above Sevenmile Canyon Boundary Spring the wash is dry except during extreme precipitation events. Surface flow in Sevenmile Canyon is only present briefly following significant precipitation events. A few isolated pools in the canyon below Sevenmile Canyon Boundary Sprring are perennial or near-perennial.

Courthouse Wash can be divided into three geomorphic segments. Above Courthouse Wash Boundary Spring, the wash is dry and forms a broad, gently sloped swale underlain by up to about 50 feet (15 m) of alluvial and eolian deposits (Doelling and Morgan, 2000). Below Courthouse Wash Boundary Spring, Courthouse Wash is a steep-sided, narrow, flat-bottomed canyon cut into and through the Moab and Slick Rock Members. From Arches Highway to its confluence with the Colorado River, Courthouse Wash crosses a broad, relatively flat plain and then becomes a steep-sided canyon cut into the Navajo Sandstone, Kayenta Formation, and Wingate Sandstone.

Data from gauging stations at Arches Highway (1958-66) and near the Colorado River (1951-57 and 1967-86) show that streamflow in Courthouse Wash is highly variable (figure 11) (U.S. Geological Survey, 2002b). We believe that streamflow is controlled by (1) spring discharge, (2) interception of surface runoff, and (3) transmission losses from evaporation, transpiration, and seepage into relatively permeable streambed alluvium below the channel. Streamflow below Courthouse Wash Boundary Spring is perennial along most of the wash, and streambed sediments are saturated close to the ground surface where surface flow is absent. Ground water from springs and seeps along the canyon walls provides the base flow for the perennial reaches of Courthouse Wash. Evaporation from the alluvium and transpiration by phreatophytes reduce the flow. Near the Colorado River the streamflow is more consistent than at Arches Highway (figure 11), because ground water in the streambed is forced to the surface by bedrock.

The mean annual streamflow at the U.S. Geological Survey (USGS) gauging station on Courthouse Wash near the Colorado River (1951-57 and 1967-86) was about 1.9 cubic feet per second (0.05 $m^3/s$). The average mean streamflow at the USGS gauging station near the Arches Highway crossing

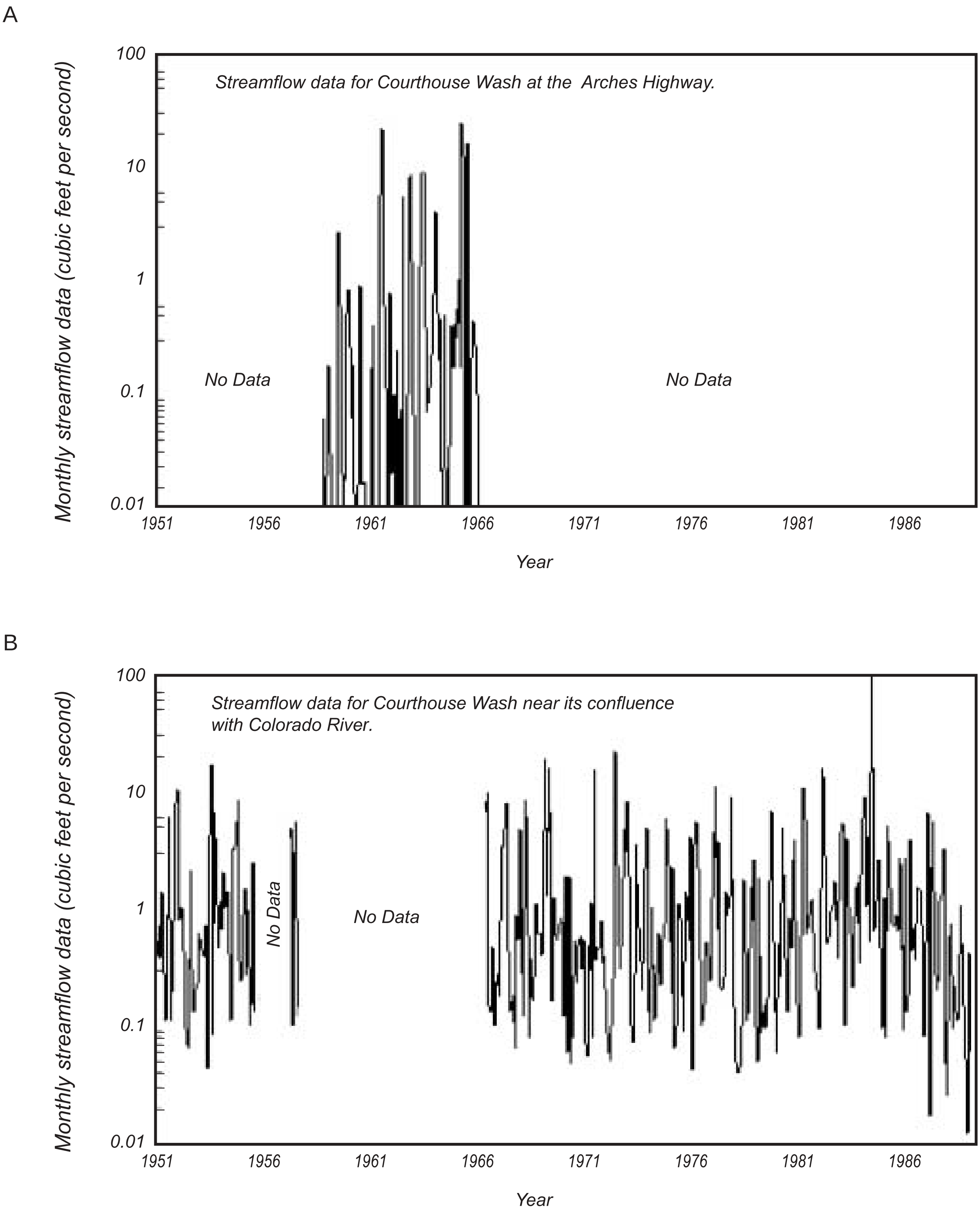



**Figure 11.** *Hydrographs of Courthouse Wash (from U.S. Geological Survey, 2002b). A. Hydrograph from gauging station at Arches Highway. B. Hydrograph from gauging station near the confluence with the Colorado River. See figure 4 for locations.*

of Courthouse Wash (1958-66) was about 1.5 cubic feet per second (0.04 $m^3/s$). We interpret the short record at the Arches Highway crossing to indicate problems with that gauging station, and think that the streamflow data from the gauging station near the confluence with the Colorado River is more reliable.

More than 50 percent of the mean monthly streamflow in Courthouse Wash occurs between July and October, when the summer and early fall thundershowers occur. The base flow of Courthouse Wash is about 0.07 cubic feet per second (0.002 $m^3/s$), determined from flow data from the gauging station near the Colorado River during late fall and early winter.

## Ground Water

### Recharge

The ground-water recharge rate is an important component of any ground-water flow system, but is difficult to quantify in arid areas where the net water flux is low. We estimate the percentage of annual precipitation that recharges the Moab Member aquifer in the study area based on the temporal distribution of annual precipitation in the study area, aquifer characteristics, and comparison with previous studies.

Our evaluation of the study area indicates that infiltration of precipitation is the only form of recharge to the Moab Member aquifer. Potential sources of this recharge include rainfall and snowmelt. Extreme storm events and flash floods bring large quantities of water into the recharge area for short durations. Some water from these events infiltrates through the exposed rock and surficial deposits, but much flows over land to surface drainages. Infiltration of snowmelt is a more efficient recharge mechanism, because the percolation rate is slower and distributed over a longer time period, and occurs when evapotranspiration rates are lower. Water not lost by evapotranspiration or surface runoff is available for infiltration.

About 9 inches (23 cm) of precipitation falls on the study area annually; slightly less than half of this total falls during October to March (table 1), when evapotranspiration is lowest. Precipitation falling on outcrop, ephemeral surface flow, water stored in pools or in surficial deposits, and snowmelt may percolate downward into the Moab Member aquifer.

Infiltrating water moves along fractures and through the sandstone matrix. Based on the relatively abundant fractures, high matrix porosity, and presence of permeable eolian sand deposits in topographic lows, the recharge potential for the Moab Member aquifer in the study area is high; however, the amount of precipitation available for recharge is low. We estimate that about 10 percent of the precipitation that falls between October and March recharges the Moab Member aquifer. This value represents about 5 percent of the total precipitation that falls on the study area, or about 0.5 inch (1 cm) per year.

Our estimate of the percentage of annual precipitation that infiltrates to the Moab Member aquifer is consistent with previous work in southwestern Utah. Price and Arnow (1974) estimated that 4 percent of the average annual precipitation in the Colorado River basin recharges shallow aquifers. Rush and others (1982) estimated a long-term annual recharge rate for rocks at depth of approximately 3 percent of the precipitation in the elevation range of 5,000 to 7,000 feet (1,500-2,100 m), based on empirical methods developed by Eakin and others (1951) for desert precipitation recharge. Avery (1986) assumed that 5 percent of mean annual precipitation becomes recharge to bedrock aquifers in San Juan County, Utah.

### Aquifers

**Regional:** Ground water in central Grand County resides in two aquifer systems: a regional, deep system that provides ground water to the Colorado River, and a shallow, mostly water-table system that supplies water to the Courthouse-Sevenmile spring system and other similar springs. In general, rocks are saturated below the altitude of the Colorado River, and the elevation of the regional potentiometric surface increases with distance from the Colorado River and its tributaries. The regional, deep aquifer system receives recharge along the divides of the major highlands, and ground-water flow is toward the Colorado River.

**Study area:** In the study area, strata above the Dewey Bridge Member of the Carmel Formation comprise the shallow aquifer system, and strata below the Dewey Bridge Member comprise the deep, regional aquifer system. The Cedar Mountain, Morrison, Curtis, Entrada, Navajo, Wingate, and Cutler Formations yield water to springs and wells in central Grand County (table 2). The quantity and quality of water discharged from these units vary with depth, composition, and hydrogeologic setting. The total-dissolved-solids concentration of water issuing from springs and water wells in the study area is generally less than 2,000 mg/L, whereas water from petroleum-test wells typically has total-dissolved-solids concentrations greater than 20,000 mg/L (Blanchard, 1990, and references therein).

The flow path of shallow ground water in the Courthouse Wash-lower Sevenmile Canyon area probably mimics surface-drainage patterns, characterized by flow toward the canyons. Factors controlling the direction, rate, and quantity of water moving through the shallow aquifer system in the study area are: (1) local hydrostratigraphy, (2) aquifer structure, (3) the topography of the land surface, and (4) the quantity of precipitation that infiltrates through the rock to recharge the ground-water system.

All but two springs and seeps discharging to Courthouse Wash and lower Sevenmile Canyon in the study area issue from the Moab Member aquifer (figure 12), which is composed of part of the Moab Member of the Curtis Formation. The Slick Rock Member of the Entrada Sandstone underlies the Moab Member and comprises the Slick Rock Member aquifer (figure 6). Blanchard (1990), Freethey and Cordey (1991), and previous workers did not distinguish the Moab and Slick Rock Member aquifers, referring to them together as the Entrada aquifer.

The Moab Member of the Curtis Formation consists of pale tan to white, fine- to medium-grained, well-sorted, cross-bedded sandstone that is moderately to well indurated by calcite cement, and is about 80 to 125 feet (24-38 m) thick (figures 6 and 8C). The sandstone is moderately densely jointed in most places, although joint density increases near the Moab fault. The Moab Member is stratigraphically bounded above by siltstone and fine-grained sandstone of the Summerville Formation and the Tidwell Member of the Mor-

***Table 1.*** *Monthly maximum, minimum, and average temperatures and average precipitation at weather stations in and adjacent to the study area (based on data from the National Weather Service, 2002). See figure 10 for map.*

| | **Arches National Park HQ** | | | | **Thompson** | | | | **Moab** | | | | **Canyonlands (The Neck)** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 4,130 feet elevation (1,259 m) | | | | 5,151 feet elevation (1,570 m) | | | | 3,967 feet elevation (1,209 m) | | | | 5,899 feet elevation (1,798 m) | | | |
| | 1980-2000 | | | | 1948-1994 | | | | 1893-1992 | | | | 1965-2000 | | | |
| Month | Maximum Temp °F | Minimum Temp °F | Average Temp °F | Average Precip *(inches)* | Maximum Temp °F | Minimum Temp °F | Average Temp °F | Average Precip *(inches)* | Maximum Temp °F | Minimum Temp °F | Average Temp °F | Average Precip *(inches)* | Maximum Temp °F | Minimum Temp °F | Average Temp °F | Average Precip *(inches)* |
| Jan | 42.8 | 20.0 | 31.4 | 0.58 | 37.1 | 14.6 | 25.9 | 0.8 | 42.0 | 18.0 | 30.0 | 0.56 | 36.8 | 20.1 | 28.5 | 0.51 |
| Feb | 50.9 | 26.7 | 38.8 | 0.44 | 45.5 | 22.3 | 33.9 | 0.53 | 51.8 | 25.5 | 38.7 | 0.43 | 44.0 | 25.9 | 35.0 | 0.41 |
| Mar | 62.0 | 35.5 | 48.8 | 0.85 | 55.3 | 29.7 | 42.5 | 0.86 | 51.9 | 34.2 | 48.0 | 0.85 | 53.3 | 32.4 | 42.9 | 0.81 |
| Apr | 70.2 | 41.9 | 56.1 | 0.84 | 66.0 | 37.9 | 52.0 | 0.76 | 71.9 | 41.9 | 56.9 | 0.98 | 62.0 | 38.6 | 50.3 | 0.79 |
| May | 80.9 | 51.1 | 66.0 | 0.76 | 75.6 | 47.0 | 61.3 | 0.88 | 82.3 | 50.1 | 66.2 | 0.72 | 73.1 | 48.5 | 60.8 | 0.79 |
| Jun | 92.3 | 60.4 | 76.4 | 0.43 | 86.9 | 57.1 | 72.0 | 0.43 | 93.1 | 57.5 | 75.3 | 0.48 | 84.2 | 59.0 | 71.6 | 0.48 |
| Jul | 98.1 | 66.9 | 82.5 | 0.90 | 93.1 | 63.9 | 78.5 | 0.69 | 99.1 | 64.1 | 81.6 | 0.83 | 90.3 | 65.1 | 77.7 | 1.02 |
| Aug | 96.1 | 65.9 | 81.0 | 0.99 | 90.4 | 61.5 | 76.0 | 1.0 | 96.5 | 62.8 | 79.7 | 0.88 | 88.1 | 63.2 | 75.7 | 0.83 |
| Sep | 86.6 | 55.5 | 71.1 | 0.80 | 81.6 | 52.6 | 67.1 | 0.94 | 87.3 | 52.8 | 70.0 | 0.75 | 78.6 | 54.6 | 66.6 | 0.87 |
| Oct | 72.6 | 41.6 | 57.1 | 1.33 | 69.5 | 41.1 | 55.3 | 1.07 | 74.4 | 40.8 | 57.6 | 1.16 | 64.8 | 42.8 | 53.8 | 1.22 |
| Nov | 56.2 | 31.0 | 43.6 | 0.69 | 52.1 | 28.2 | 70.2 | 0.64 | 58.3 | 30.6 | 44.5 | 0.74 | 48.6 | 30.8 | 39.7 | 0.74 |
| Dec | 44.0 | 22.3 | 33.2 | 0.45 | 40.4 | 18.1 | 29.3 | 0.59 | 45.1 | 21.4 | 33.2 | 0.65 | 37.9 | 21.5 | 29.7 | 0.61 |
| | Average Temperature °F 57.2 | | | | Average Temperature °F 55.3 | | | | Average Temperature °F 56.8 | | | | Average Temperature °F 50.2 | | | |
| | Total Annual Precipitation 9.06 | | | | Total Annual Precipitation 9.19 | | | | Total Annual Precipitation 9.04 | | | | Total Annual Precipitation 9.08 | | | |

*Table 2. Geologic and hydrologic characteristics of aquifers in the study area. Compiled from Blanchard (1990) and Doelling and Morgan (2000).*

| Geologic Unit[1] | Map Symbol | Thickness in feet (m) | Lithology | General Hydrologic Characteristics | Yield (gallons per minute) | Water Quality[2] | |
|---|---|---|---|---|---|---|---|
| | | | | | | Total Dissolved Solids (mg/L) | Chemistry Type |
| Cedar Mountain | Kcm | 120-200 (37-61) | Interbedded sandstone, conglomeratic sandstone, and mudstone | Sandstone and conglomerate yield small amounts of water to springs and wells | Springs: < 1<br>Wells: <1 | Spring: 1,020<br>Well: 1,470 | Calcium magnesium sodium sulfate bicarbonate |
| Brushy Basin Member of Morrison Formation | Jmb | 295-450 (90-135) | Mudstone, fine-grained sandstone, and conglomeratic sandstone | Yields small amounts of water to springs and wells | Springs: < 1<br>Wells: < 1 | Spring: 1,020 | Calcium magnesium sodium sulfate bicarbonate |
| Salt Wash Member of Morrison Formation | Jms | 130-300 (40-90) | Interbedded sandstone, conglomerate, and siltstone | Sandstone and conglomerate yield small amounts of water to springs and wells | Springs: < 1<br>Wells: < 1 | Spring: 1,160 | Calcium magnesium sodium sulfate bicarbonate |
| Moab Member of Curtis Formation[3] | Jctm | 70-110 (21-34) | Cross-bedded, well-sorted, fine- to medium-grained sandstone, moderately indurated with calcite cement | Yields abundant water to springs and wells | Springs: 0.1-11.1 | Springs: 143-157 | Calcium carbonate; hard to very hard |
| Slick Rock Member of Entrada Sandstone | Jes | 180-400 (55-122) | Cross-bedded, well-sorted, fine- to medium-grained sandstone, weakly to moderately indurated with calcite cement | Yields moderately abundant water to springs and wells | No data | Well: 300 | Calcium carbonate; hard to very hard |
| Navajo Sandstone | Jn | 165-800 (50-244) | Cross-bedded, well-sorted, fine-grained sandstone, weakly to moderately indurated with calcite cement | Yields abundant water to springs and wells | Springs: <1-5 | Springs: 102-350<br>Well: 210-360 | Calcium bicarbonate to calcium magnesium bicarbonate |
| Wingate Sandstone | Jw | 250-400 (76-122) | Cross-bedded, well-sorted, fine-grained sandstone, indurated with calcite cement | Yields abundant water to springs and wells | Springs: 10-240 | Springs: 161-174<br>Well[4]: 280-45,000 | Calcium magnesium bicarbonate; moderately hard to hard |
| Arkosic member of Cutler Formation | Pc | 0-4,000 (0-1,220) | Cross-bedded, medium to coarse-grained sandstone and minor conglomerate. | Yields small amounts of water to wells | Wells: 1-40 | Wells: 1,420-3,450 | Calcium magnesium sulfate; very hard |

Notes

1. See figure 6 and appendix for additional information. Unit thicknesses are from Doelling and Morgan (2000) and represent ranges from a wider area than shown on the cross sections in this report.
2. Data from petroleum wells not included. Total-dissolved-solids concentrations of water from petroleum wells range from about 2,000 to over 100,000 mg/L (Blanchard, 1990, p. 28).
3. Formerly mapped as a member of the Entrada Sandstone; see Doelling (2001) for an explanation of nomenclature revision. Blanchard (1990) does not differentiate the Moab Member of the Curtis Formation (considered a member of the Entrada Sandstone at the time of his report) from the underlying Slick Rock Member of the Entrada Sandstone. Assignment of Blanchard’s (1990) data to the Moab or Slick Rock Member is based on work done as part of this study.
4. Blanchard (1990) reports a measured value of 45,000 mg/L for one shallow well in the Wingate aquifer. He suggests that this anomalous value is caused by an upward gradient moving ground water from the salt-rich Paradox Formation and/or underlying formations into the Wingate aquifer here.

rison Formation (combined as unit Jsmt on figure 7 and plate 1), and is bounded below by the Slick Rock Member aquifer (figures 6 and 8C). The Summerville and Morrison Formations likely form an aquitard where present, based on their lithology. The contact between the Moab Member of the Curtis Formation and the Slick Rock Member of the Entrada Sandstone is an unconformity marked by a change from pale gray-tan of the Moab Member above to the reddish-brown hues of the Slick Rock Member below (figures 6 and 8C). The unconformity is easily eroded in places, forming a subhorizontal cleft in the canyon wall (figure 2B). Where exposed and accessible, the top surface of the Slick Rock Member is coated with a white, fine-grained mineral deposit, likely precipitated from ground water when the contact was below the water table, that forms an impermeable barrier below the Moab Member (Blanchard, 1990)

Within the study area, the boundaries of the Moab Member aquifer are erosional to the northeast where it is exposed along the southwest flank of the Salt Valley anticline, and structural to the southwest where it is cut by the Moab fault (figure 7). Within its outcrop area the Moab Member aquifer is partitioned into three hydrologically isolated compartments by Courthouse Wash and Sevenmile Canyon, which have cut down through the Moab Member into the Slick Rock Member.

The Moab Member aquifer is under both confined and unconfined conditions. At the springs and where the Moab Member is exposed, ground-water levels in the aquifer are below the top of the Moab Member and fluctuate in response to recharge rates. Discharge is thus partially controlled by the recharge rate, with higher recharge resulting in a higher water level in the aquifer, thus higher hydraulic gradients and greater flow to the springs. The Moab Member aquifer is under confined conditions where it underlies the Summerville and Morrison Formations, which are relatively impermeable and obstruct vertical ground-water movement. Thus infiltration of precipitation to the Moab Member aquifer occurs chiefly where the aquifer is exposed.

The Slick Rock Member of the Entrada Sandstone consists of orange- to reddish-brown, fine-grained, well-sorted, planar- to cross-bedded sandstone that is moderately to weakly indurated with calcite cement (figures 6, 8C, and 8D) and is about 180 to 400 feet (55-120 m) thick. Although the Slick Rock Member is an aquifer in much of southern Utah (Blanchard, 1990; Freethey and Cordey, 1991), in the study area its hydraulic conductivity is apparently lower than that of the Moab Member, presumably due to lower fracture density and/or overall finer average grain size. The Dewey Bridge Member of the Carmel Formation, composed of muddy siltstone to fine-grained sandstone, forms an aquitard below the Slick Rock Member (figures 6 and 8D).

Jobin (1962) estimated a hydraulic conductivity value of about 1.1 feet per day (0.34 m/d) and a transmissivity value of about 150 square feet per day (14 $m^2$/d) for the undivided Entrada aquifer, based on laboratory measurements on three core samples from outcrops northwest of Moab. These values are relatively high for a sandstone aquifer (Freeze and Cherry, 1979). Jobin's (1962) tables and maps do not give sufficient detail to locate his sample sites or to distinguish whether these samples were from the Moab Member or Slick Rock Member aquifer.

### Wells and Water Levels

At least 16 water wells are in the study area (table 3; figures 3 and 7; plate 1). Seven wells southwest of the Moab fault near U.S. Highway 191 (wells 9 through 15, table 3) are screened in the Permian Cutler Formation. Three wells northeast of the Moab fault are screened in the Moab Member of the Curtis Formation (wells 5 through 7, table 3), one well is screened in the Slick Rock Member of the Entrada Sandstone (well 8, table 3), and two wells are screened in the Morrison Formation (wells 3 and 4, table 3). Useful test data are available only for well 9 (table 3); it is screened in the Cutler Formation, and had a specific capacity of 5.8 gallons per minute per foot of drawdown (72.1 L/min/m) (Utah Division of Water Rights, 2002).

Static water levels are available for 10 of the wells in the study area (table 3). Different workers collected these data at different times, so they cannot be used to construct reliable water-level contours. More than one reading exists for only one well (well 4, table 3), which is monitored by the U.S. Geological Survey (2002a).

Water levels in wells screened in the Moab Member of the Curtis Formation (wells 5, 6, and 7, table 3) are 20 to 98 feet (6-30 m) higher than the elevation of Courthouse Wash Boundary Spring (4,300 feet [1,311 m]), 0 to 78 feet (0-24 m) higher than the elevation of Sevenmile Canyon Boundary Spring (4,320 feet [1,317 m]), and 100 to 178 feet (30-55 m) higher than the elevations of springs in the eastern spring group (4,220 to 4,240 feet [1,286-1,292 m]). These elevation differences indicate an east- to southeast-sloping potentiometric surface in the Courthouse Wash-Sevenmile Canyon area, and that ground water flows from the area of the wells toward Courthouse Spring.

Static water levels in wells 5 through 7, all screened in the Moab Member (table 3), ranged from about 4,320 to 4,398 feet (1,317-1,341 m) elevation when the wells were drilled. These water levels are about 20 to 98 feet (6-30 m) higher than Courthouse Wash Boundary Spring (elevation 4,300 feet [1,311 m]) and the other springs of the northern group, indicating that some ground water flows from the confined Moab Member aquifer west of Courthouse Wash to Courthouse Wash Boundary Spring. The wells are not hydrologically connected to Sevenmile Canyon Boundary Spring or the eastern spring group, due to the intervening canyons.

Water levels are from 100 to 195 feet (30-59 m) lower northeast of the Moab fault than they are southwest of the fault (compare water-level elevations in wells 5 through 8 to those in wells 9 and 13). Because these measurements were made during different months of different years, they are not useful for calculating ground-water gradients, but they suggest that the Moab fault is a hydrologic boundary to horizontal ground-water flow in the shallow aquifer. This inference places important limitations on the possible recharge areas for Courthouse Wash and Sevenmile Canyon Boundary Springs.

### Springs

Springs in the study area form three geographic groups: the western, eastern, and northern groups (table 4; plate 1). The northern group includes Courthouse Wash Boundary Spring and two unnamed springs along the west side of

***Table 3.*** *Records for water wells in the study area.*[1]

| ID[2] | Location[3] | Well Diameter (in) | Well Depth (ft) | Screened Interval (ft) | Static Water Level (ft)[4]; Measure Date | Ground Surface Elevation (ft)[5] | Elevation of Static Water Level (ft)[6] | Producing Unit[7] |
|---|---|---|---|---|---|---|---|---|
| 1 | N 350 W 950 SE 23S 20E 31 | 6.0 | 1200 | nd | 85; 5/26/96 | 4570 | 4485 | nd |
| 2 | N 650 E 450 NW 24S 20E 5 | 7.0 | 1160 | 2 to 1078 | 70; 9/1/85 | 4550 | 4480 | Kd-Jctm |
| 3 | S 1012 W 766 E4 24S 20E 16 | 8.6 | 45 | nd | nd | 4430 | nd | Jmb |
| 4 | S 4015 W 750NE 24S 20E 22 | 8.3 | 70 | 46 to 70 | 14.5; 3/3/00 | 4410 | 4395 | Jmb |
| 5 | N 640 W 550 E4 24S 20E 34 | 6.6 | 300 | - | 162; 10/10/78 | 4560 | 4398 | Jctm |
| 6 | N 100 W 480 E4 24S 20E 34 | 6.3 | 400 | 320 to 400 | 220; 6/21/99 | 4560 | 4340 | Jctm |
| 7 | S 2400 E 600 NW 24S 20E 35 | 7.0 | 340 | 280 to 340 | 240; 6/30/93 | 4560 | 4320 | Jctm |
| 8 | 24S 20E 35 | 4.5 | 388 | 328 to 388 | 200; 7/10/94 | 4550 | 4350 | Jes |
| 9 | N 5225 E 858 SW 25S 20E 2 | 6.0 | 200 | 150 to 200 | 15; 2/26/95 | 4530 | 4515 | Pc |
| 10 | N 2700 E 50 SW 25S 20E 2 | 6.0 | 200 | nd | nd | 4550 | nd | Pc |
| 11 | N 2700 E 250 SW 25S 20E 2 | 6.0 | 600 | nd | nd | 4550 | nd | Pc |
| 12 | N 2700 E 530 SW 25S 20E 2 | 8.8 | 100 | nd | nd | 4550 | nd | Pc |
| 13 | N 2700 E 750 SW 25S 20E 2 | 8.8 | 125 | 75 to 105 | 48; 2/16/95 | 4550 | 4502 | Pc |
| 14 | N 1100 W 850 SE 25S 20E 2 | 5.0 | 260 | nd | nd | 4590 | nd | Pc |
| 15 | N 1500 W 20 SE 25S 20E 2 | 6.0 | 550 | 155 to 230 | nd | 4540 | nd | Pc |
| 16 | N 500 E 700 SW 24S 20E 19 | 7.0 | 665 | nd | 200; 1/31/79 | 4780 | 4580 | nd |

Notes

nd - no data

1. Data for wells 1-11 from Utah Division of Water Rights (2002); data for wells 12-16 from U.S. Geological Survey (2002a), except as noted below.
2. Corresponds to well numbers on figures 3 and 7 and plate 1.
3. Well locations are in point of diversion notation (figure A.3).
4. Depth below wellhead.
5. Estimated by the authors from 7-1/2 minute topographic maps with 20-foot contour intervals.
6. Equals ground surface elevation minus static water level.
7. Determined by the authors from geologic cross sections, maps, and well logs. Unit abbreviations: Kd, Dakota Formation; Jctm, Moab Member of Curtis Formation; Jes, Slick Rock Member of Entrada Sandstone; Pc, arkosic member of Cutler Formation. See figure 6 and plate 1 for stratigraphy and unit descriptions.

***Table 4.*** *Locations and elevations of springs in the Courthouse-Sevenmile spring system. Data from U.S. Geological Survey Merrimac Butte 7½-minute topographic map, field work by the authors, and National Park Service data.*

| **Name** | **Location[1]** | **Elevation ft (m)** |
|---|---|---|
| **Western spring group** | | |
| Sevenmile Canyon Boundary Spring | (D-25-20) 1aad-S1 | 4,320 (1,317) |
| Poison Ivy Spring | (D-24-21) 31ccc-S1 | 4,260 (1,298) |
| unnamed | (D-25-21) 6bbb-S1 | 4,260 (1,298) |
| unnamed | (D-25-21) 6adc-S1 | 4,300 (1,311) |
| unnamed | (D-25-21) 6dda-S1 | 4,280 (1,304) |
| **Eastern spring group** | | |
| Sleepy Hollow Spring | (D-24-21) 31dab-S1 | 4,220 (1,286) |
| unnamed | (D-24-21) 31dab-S2 | 4,220 (1,286) |
| Mossy Pool Spring | (D-25-21) 5bbb-S1 | 4,240 (1,292) |
| Antler Pool Spring | (D-25-21) 5abb-S1 | 4,240 (1,292) |
| unnamed | (D-25-21) 5bda-S1 | 4,240 (1,292) |
| Willow Spring | (D-24-21) 20cac-S1 | 4,600 (1,402) |
| **Northern spring group** | | |
| Courthouse Wash Boundary Spring | (D-24-21) 30cbb-S1 | 4,300 (1,311) |
| unnamed | (D-24-21) 31bba-S1 | 4,300 (1,311) |
| unnamed | (D-24-21) 31bda-S1 | 4,280 (1,304) |

Notes

[1] U.S. Geological Survey notation; see figure A.3 for explanation.

Courthouse Wash north of its confluence with lower Sevenmile Canyon. The western group is along the south side of lower Sevenmile Canyon and the west side of Courthouse Wash below the confluence with Sevenmile Canyon, including Sevenmile Canyon Boundary Spring, Poison Ivy Spring, several unnamed springs, and numerous seeps. The eastern group is along the east side of Courthouse Wash, including Sleepy Hollow, Mossy Pool, and Antler Springs, and several unnamed springs and seeps.

Based on their locations along opposite sides of Courthouse Wash and Sevenmile Canyon, the eastern and western spring groups must have different source areas and hydrologic systems. The recharge area for the western group must be southwest of lower Sevenmile Canyon and Courthouse Wash, and the recharge area for the eastern group must be northeast to east of Courthouse Wash. The recharge area for the northern group is the triangular area north of lower Sevenmile Canyon and west of Courthouse Wash, and Courthouse Wash Boundary Spring also likely receives recharge from the confined Moab Member aquifer to the north and northwest. In a later section, we provide more specific estimates for the recharge areas contributing to spring flow.

Sevenmile Canyon Boundary, Poison Ivy, and Sleepy Hollow Springs are contact springs located in alcoves, issuing from the base of the Moab Member of the Curtis Formation (figure 12). The alcoves formed where ground-water outflow has concentrated, leading to enhanced weathering and erosion by undermining and collapse at the site of the outflow. Courthouse Wash Boundary Spring and the next spring downstream in the northern spring group are diffuse-contact springs that issue from the top of the Moab Member.

Blanchard (1990) published flow, specific-conductance, and chemical data for samples collected in 1970 by the National Park Service for three springs in the eastern group (table 4). The flow from these springs ranged from 6 to 11 gallons per minute (0.4-0.7 L/s), and total-dissolved-solids concentrations ranged from 143 to 157 mg/L.

For this study, the National Park Service measured spring discharge rates at Courthouse Wash Boundary Spring, Sevenmile Canyon Boundary Spring, Sleepy Hollow Spring, and Poison Ivy Spring monthly during 2001 and 2002 (figure 13). The discharge at Courthouse Wash Boundary Spring and Sleepy Hollow Spring was more variable than at Sevenmile Canyon Boundary Spring and Poison Ivy Spring. Peak discharges for all of the measured springs occurred in the winter and minimum discharges occurred in the summer (figure 13). Sleepy Hollow Spring and Courthouse Wash Boundary Spring experienced increased flow in July and August 2001, respectively, in contrast to the other two springs measured.

A

B

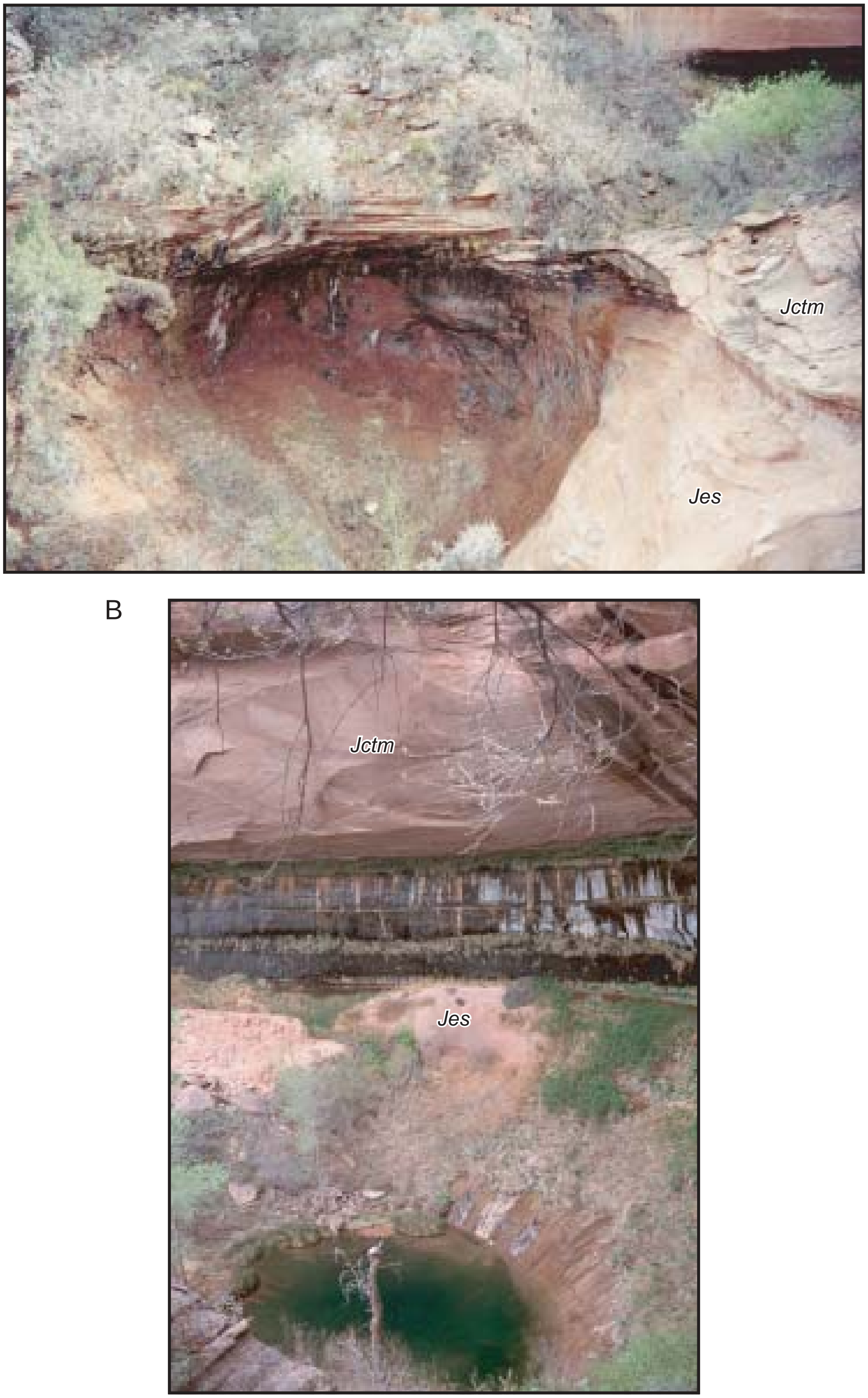



***Figure 12.*** *Springs and seeps issuing from the contact between the Moab Member of the Curtis Formation (Jctm) and the Slick Rock Member of the Entrada Sandstone (Jes) in Courthouse Wash and lower Sevenmile Canyon. A. Unnamed spring in an alcove in the south wall of lo wer Sevenmile Canyon about 0.75 mile (1.2 km) west of Sevenmile Canyon Boundary Spring. B. Sleepy Hollow Spring in an alcove in the north wall of Courthouse Wash about 1 mile (0.6 km) southeast of Courthouse W ash Boundary Spring.*

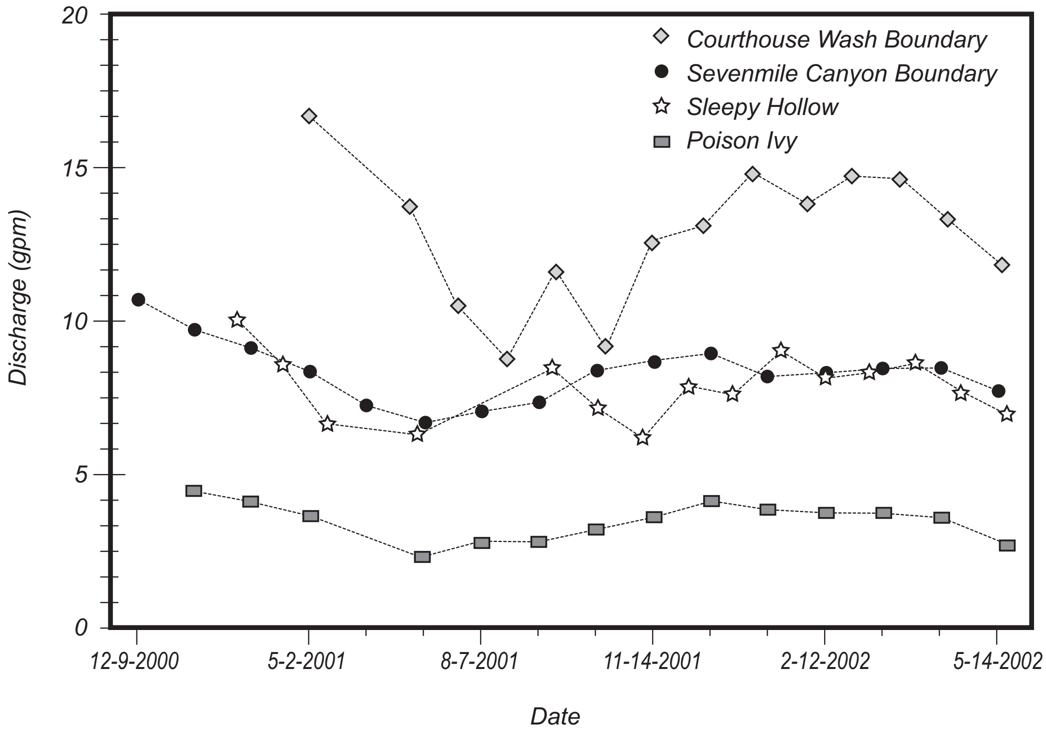



***Figure 13.*** *Instantaneous monthly flow for springs monitored in this study (based on unpublished National Park Service data).*

Courthouse Wash Boundary Spring showed a wider range in flow (from about 17 to 8.5 gallons per minute) than the other three springs measured; its lowest flows were in July and September 2001, separated by increased flow in August 2001. This discharge pattern indicates that the annual recharge is significant compared to the water-storage capacity of the aquifer supplying flow to Courthouse Wash Boundary Spring.

The flow records for Sevenmile Canyon Boundary Spring and Poison Ivy Spring, both of the western group, are similar, with peak flow in December through March 2001 and minimum flow in July 2001. Sleepy Hollow, of the eastern group, ranged from about 10 to 6 gallons per minute, with peak flow in December through March, and minimum flow in June and September 2001. This discharge pattern indicates that the water-storage capacity of the aquifer supplying these springs is large compared to their annual recharge.

The Moab Member aquifer acts as a ground-water reservoir of limited capacity, analogous to a surface-water reservoir. As water is added to the reservoir a greater proportion of the Moab Member aquifer is saturated and ground-water levels within it rise. The fluctuation of ground-water levels affects the discharge of the springs in the Courthouse-Sevenmile spring system differently based on their locations within the aquifer. Courthouse Wash Boundary Spring issues from the top of the Moab Member aquifer, so its discharge is more sensitive to changes in water levels within the aquifer because it is closer to the top of the saturated zone and the percent change in head at this spring due to water-level fluctuations in the aquifer is relatively high. The other springs issue from the base of the Moab Member aquifer, so their discharges are less sensitive to fluctuations in ground-water levels within the aquifer.

The increased discharge from Courthouse Wash Boundary Spring and Sleepy Hollow Spring during summer may reflect release of water from storage in adjacent alluvium and pools following intense rainstorms that are common during the summer monsoon season. The measuring points for Courthouse Wash Boundary Spring and Sleepy Hollow Spring are both downstream from the main discharge areas, so flow at these points could be affected by factors other than discharge from bedrock. The measuring points for Sevenmile Canyon Boundary and Poison Ivy Springs, in contrast, are much closer to the discharge points, so these measurements do not reflect the postulated release from storage.

The total amount of ground-water discharge in the study area is unknown, although at least 60 gallons per minute (3.8 L/s) can be estimated based on maximum measured spring discharge. Base flow is at least 0.07 cubic feet per second (0.002 $m^3$/s) in the perennial reaches of Courthouse Wash.

## Geochemistry

### Introduction

The chemical character of ground water is principally related to: (1) chemical character of the water as it enters the zone of saturation; (2) distribution, solubility, texture, and adsorption capacity of minerals in the rocks; (3) degree of fracturing, porosity, and permeability of the rocks; and (4) the flow path of the water (Hem, 1985). Total-dissolved-solids (TDS) concentrations in ground water in the Colorado Plateau in Utah ranges from less than 100 to more than 390,000 mg/L (Feltis, 1966). Aquifers generally yield fresh water from shallow sources, but the ground water becomes more saline with increasing depth as a result of longer residence time in rocks containing relatively soluble minerals. Water samples from springs issuing from the Moab Member aquifer and similar formations in the Colorado Plateau have TDS concentrations ranging from 204 to 14,300 mg/L, averaging 5,790 mg/L (Feltis, 1966). Water samples from the Moab Member have low TDS concentrations, because the sandstone has low soluble-mineral content.

We sampled ground water discharging from Courthouse Wash Boundary Spring and Sevenmile Canyon Boundary Spring quarterly from June 2001 to May 2002, to interpret the flow path feeding these springs and to establish baseline data for long-term monitoring of water quality. Sampling was performed several weeks after precipitation events, to avoid contamination by surface water. In interpreting the data we also considered chemical data from previous work (Blanchard, 1990) (tables 4 and 5).

### Field Measurements

We measured the temperature, specific conductance, dissolved oxygen, and pH of water from Courthouse Wash and Sevenmile Canyon Boundary Springs in the field for this study (table 6). The temperature of Courthouse Wash Boundary Spring water was measured at the collection point, where flowing water is most concentrated. Sevenmile Canyon Boundary Spring water was measured near the bedding planes where the water flows out of the rock. Ambient air temperature was measured at the same time as water temperature to check for temperature equilibration. Water temperature varied from 10.2 to 33.1°C (50-92°F) for Courthouse Wash Boundary Spring and from 3.1 to 24.6°C (38-76 °F) for Sevenmile Canyon Boundary Spring (table 6 and figure 14). The temperature pattern for both springs is similar to the temperature profile at the Park Headquarters (figure 14), suggesting that the temperature variations observed in the spring waters reflect normal seasonal variations.

Specific conductance varied slightly, ranging from 447 to 644 µs/cm for Courthouse Wash Boundary Spring and from 186 to 234 µs/cm for Sevenmile Canyon Boundary Spring; one measured value of 537 µs/cm is suspect (table 6 and figure 15). Water from the springs is classified as fresh based on specific conductance (Feltis, 1966). The range of pH values was 8.0 to 9.6 for Courthouse Wash Boundary Spring and 7.2 to 8.4 for Sevenmile Canyon Boundary Spring (table 6; figure 15). The pH of these waters shows that they are somewhat alkaline. Dissolved oxygen ranged from 2.3 to 6.4 mg/L for Courthouse Wash Boundary Spring and from 3.5 to 8.3 mg/L for Sevenmile Canyon Boundary Spring (table 6). Our data supplement, and are consistent with, data collected by the National Park Service for Sleepy Hollow and Willow Springs (table 7).

### Analytical Data

Courthouse Wash Boundary Spring water has higher TDS, sodium, chloride, sulfate, total alkalinity, and total hardness and shows greater chemical variability than Sevenmile Canyon Boundary Spring water (table 8). Bicarbonate is the dominant anion in all analyses, but chloride is also significant at Courthouse Wash Boundary Spring. Dissolved-solids concentrations are less than 300 mg/L in water from both springs. Neither spring showed significant temporal variation in chemistry.

A trilinear diagram of major-ion concentrations (figure 16) shows that Sevenmile Canyon Boundary Spring discharges water of the calcium-bicarbonate ($Ca\text{-}HCO_3$) type, and Courthouse Wash Boundary Spring discharges water of a sodium-calcium-bicarbonate ($Na\text{-}Ca\text{-}HCO_3$) type. Sodium exceeds calcium in water from Courthouse Wash Boundary Spring, but the opposite is true at Sevenmile Canyon Boundary, Sleepy Hollow, Mossy Pool, and Antler Pool Springs (tables 5 and 8).

Calcium-to-magnesium molar ratios can be used to discern if the water has come into contact with rocks containing dolomite or calcite. Ground water having a Ca/Mg molar ratio of approximately 1 has been in contact with rocks containing predominantly dolomite, a ratio from 1 to 3 indicates contact with dolomite and calcite, and a ratio greater than 3 indicates contact with calcite (Hem, 1985). The Ca/Mg molar ratio of Courthouse Wash Boundary Spring water ranges from 1.1 to 1.45, whereas Sevenmile Canyon Boundary Spring water ranges from 5.31 to 5.75, and Sleepy Hollow, Mossy Pool, and Antler Pool spring water have values of 8.15, 8.98, and 7.23, respectively. These values represent dissolution of calcite in all of the samples, and contribution from dolomite or some other magnesium-bearing mineral in water from Courthouse Wash Boundary Spring.

Hardness is caused chiefly by calcium and magnesium and in some water by small quantities of strontium and barium. Water of the Courthouse-Sevenmile spring system is moderately hard to very hard. Hardness ranges from 143.5 to 180.6 mg/L $CaCO_3$ (hard to very hard) for Courthouse Wash Boundary Spring, 171 to 359.1 mg/L $CaCO_3$ (hard to very hard) for Willow Spring, and 107.7 to 124.8 mg/L $CaCO_3$ (moderately hard to hard) for Sevenmile Canyon Boundary Spring (tables 5 and 8). Hardness generally increases to the north. The alkalinity of Courthouse Wash Boundary Spring ranged from 162 to 203 mg/L $CaCO_3$ and Sevenmile Canyon Boundary Spring ranged from 99 to 114 mg/L $CaCO_3$ (table 8).

### Interpretation

The major-ion chemistry of samples collected during this study indicates two water types. Water from Sevenmile Canyon Boundary Spring is of the calcium-bicarbonate type, and water from Courthouse Wash Boundary Spring is of the sodium-calcium-bicarbonate type. The predominance of bicarbonate and calcium and the calcium-to-magnesium ratios in both types result from dissolution of the calcite cement in the Moab Member aquifer. The distinct chemistry of Courthouse Wash Boundary Spring indicates mixing of water similar to that supplying Sevenmile Canyon Boundary Spring and the other springs in the study area with water that has interacted with another geologic unit. The best candidates for the second source are water from the confined Moab Member aquifer west and north of Courthouse Wash Boundary Spring, and stream alluvium derived in part from the Morrison and Mancos Formations. Water from the confined Moab Member aquifer may acquire its geochemical signature either by percolation of precipitation from directly above the aquifer or during flow along the Moab fault.

The solubility of oxygen in fresh water is a function of temperature and pressure. The oxygen in the water reacts

***Table 5.*** *Chemical data for three springs along eastern Courthouse Wash (Blanchard, 1990)*[1].

| Spring Name[2] | Date Measured | Discharge (gal/min) | Temperature (°C) | Specific Conductance (σS/cm) | pH (units) | Solids, residue at 180 °C dissolved (mg/L) | Calcium, dissolved (mg/L as Ca) | Magnesium, dissolved (mg/L as Mg) | Sodium, dissolved (mg/L as Na) | Potassium, dissolved (mg/L as K) | Chloride, dissolved (mg/L as Cl) | Sulfate, dissolved (mg/L as $SO_4$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sleepy Hollow | 9/1 & 9/15/70 | 8.2 | 13.0 | 225 | 7.7 | 143 | 43 | 3.2 | 2.3 | 1.6 | 3.5 | 6.5 |
| Mossy Pool | 9/15/70 | 11.0 | 13.0 | 250 | 7.4 | 145 | 49 | 3.3 | 2.6 | 1.1 | 5.0 | 10 |
| Antler Pool | 9/15/70 | 6.0 | 12.5 | 270 | 8.0 | 157 | 49 | 4.1 | 3.8 | 1.7 | 5.0 | 12 |

| Spring Name | Fluoride, dissolved (mg/L as F) | Alkalinity, lab, (mg/L as $CaCO_3$) | Carbon dioxide, dissolved (mg/L as $CO_2$) | Silica, dissolved (mg/L as $SiO_2$) | Hardness, total (mg/L as $CaCO_3$) | Hardness, noncarbonate (mg/L as $CaCO_3$) | Arsenic, dissolved (µg/L as As) | Barium, dissolved (µg/L as Ba) | Iron, dissolved (µg/L as Fe) | Selenium, dissolved (µg/L as Se) | Strontium, dissolved (µg/L as Sr) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sleepy Hollow | 0.4 | nd | 4.2 | 10 | 120 | 0 | 0 | - | 0 | 37 | nd |
| Mossy Pool | 0.5 | nd | 9.4 | 9.5 | 140 | 0 | 0 | - | 0 | 89 | nd |
| Antler Pool | 0.5 | nd | 2.5 | 11 | 140 | 11 | 0 | - | 0 | 55 | nd |

Notes

nd - no data

1. Data were collected by the National Park Service and reported in Blanchard (1990). See plate 1 for locations.
2. See table 4 for locations and elevations.

*Table 6. Field parameters for Courthouse Wash Boundary Spring and Sevenmile Canyon Boundary Spring water. See table 4 for locations and elevations.*

| Date of Sample | Water Temperature (°C) | Specific Conductance (µS/cm) | Dissolved Oxygen (mg/L) | pH |
|---|---|---|---|---|
| **Courthouse Wash Boundary Spring** | | | | |
| December 2000 | 10.2 | 644 | 2.3 | 8.0 |
| June 2001 | 29.3 | 522 | — | 9.6 |
| August 2001 | 33.1 | 521 | 4.0 | 8.0 |
| November 2001 | 11.1 | 492 | 4.9 | 8.4 |
| February 2002 | 12.4 | 450 | 6.4 | 9.1 |
| May 2002 | 27.3 | 447 | 5.4 | 9.0 |
| **Sevenmile Canyon Boundary Spring** | | | | |
| December 2000 | 4.8 | 232 | 3.5 | 7.2 |
| June 2001 | 22.1 | 234 | — | 8.0 |
| August 2001 | 24.6 | 229 | 5.8 | 7.9 |
| November 2001 | 7.2 | 186 | 8.3 | 8.2 |
| February 2002 | 3.1 | 537 (suspect value) | 5.2 | 8.4 |
| May 2002 | 10.2 | 218 | 5.3 | 8.1 |

*Table 7. Field parameters for water fr om Sleepy Hollow and W il-low Springs, collected by the National Park Service.*

| Date | Water Temperature °C | pH | Specific Conductance µS/cm |
|---|---|---|---|
| **Sleepy Hollow Spring** | | | |
| 03-May-85 | 13.9 | 6.3 | 572 |
| 23-Jan-86 | 13 | — | 530 |
| 13-May-87 | 15.8 | 7.5 | 566 |
| 23-Aug-87 | 19.9 | 7.7 | 597 |
| 10-May-88 | 11.2 | 6.3 | 567 |
| 18-Aug-88 | 34.6 | 7.65 | 413 |
| 15-May-89 | 17.3 | 7.6 | 605 |
| 10-Aug-89 | 21.6 | 7.45 | 362 |
| 03-May-90 | 21.4 | 7.66 | 633 |
| **Willow Spring** | | | |
| 03-Jan-85 | 2.6 | — | 546 |
| 01-May-85 | 15.8 | 6.65 | 221 |
| 26-Aug-85 | 21.6 | 6.7 | 274 |
| 04-Jun-87 | 17.7 | 7.55 | 266 |
| 24-Aug-87 | 21.8 | 7.75 | 250 |
| 10-May-88 | 13.3 | 6.75 | 265 |
| 19-Aug-88 | 21.7 | 7.1 | 285 |
| 14-May-89 | 14.3 | 8.1 | 198 |
| 11-Aug-89 | 22.4 | 7.5 | 199 |
| 25-Apr-90 | 13.6 | 8.1 | 228 |

***Table 8.** Chemistry of Courthouse Wash Boundary Spring and Sevenmile Canyon Boundary Spring water (Laboratory: Utah State Department of H ealth, Division of Epidemeology and Laboratory Services).*

| Date of Sample | TDS@ 180°C (mg/L) | Calcium, Dissolved (mg/L as Ca) | Magnesium, Dissolved (mg/L as Mg) | Sodium, Dissolved (mg/L as Na) | Potassium, Dissolved (mg/L as K) | Chloride, Dissolved (mg/L as Cl) | Sulfate, Dissolved (mg/L as $SO_4$) | Fluoride, Dissolved (mg/L as F) | Total alkalinity (mg/L as $CaCO_3$) | Carbon dioxide (mg/L as $CO_2$) | Total hardness (mg/L as $CaCO_3$) | Bicarbonate (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Courthouse Wash Boundary Spring** | | | | | | | | | | | | |
| June-2001 | 175.1 | 41.5 | 17.4 | - | - | 4.7 | 80.1 | 0.28 | 202 | 2 | 175.1 | 246 |
| September-2001 | 274 | 32.3 | 15.3 | 60.2 | 2.81 | 4.44 | 63.9 | 0.27 | 162 | 2 | 143.5 | 197 |
| February-2002 | 248 | 37.9 | 20.9 | 59.1 | 3.28 | 5.26 | 90.4 | - | 203 | 2 | 180.6 | 248 |
| **Sevenmile Canyon Boundary Spring** | | | | | | | | | | | | |
| June-2001 | 134 | 36.8 | 4.2 | - | - | <3 | <20 | 0.107 | 99 | 2 | 109.1 | 121 |
| September-2001 | 152 | 42.6 | 4.49 | 3.8 | 1.21 | <3 | <20 | 0.114 | 114 | 2 | 124.8 | 139 |
| February-2002 | 76 | 36.6 | 3.99 | 3.72 | 1.31 | <3 | <20.0 | - | 102 | 2 | 107.7 | 125 |

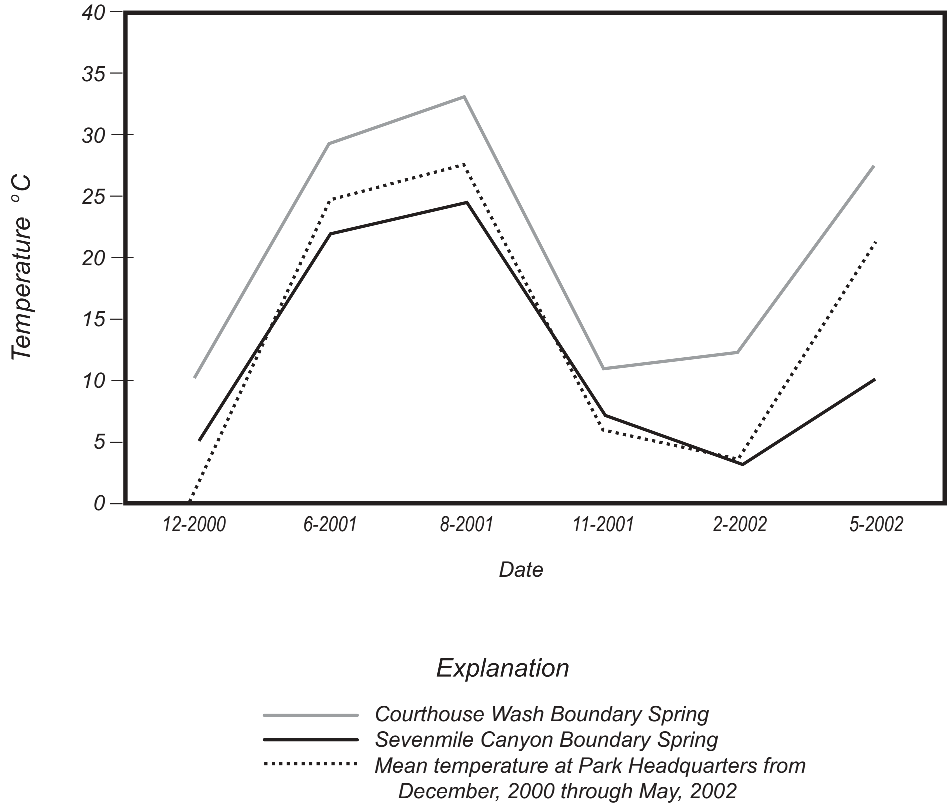



***Figure 14.*** *Water temperature records for Courthouse Wash Boundary Spring and Sevenmile Canyon Boundary Spring, and mean air temperatures at Arches National Park headquarters (data for mean air temperatures from National Weather Service, 2002; other data from this report).*

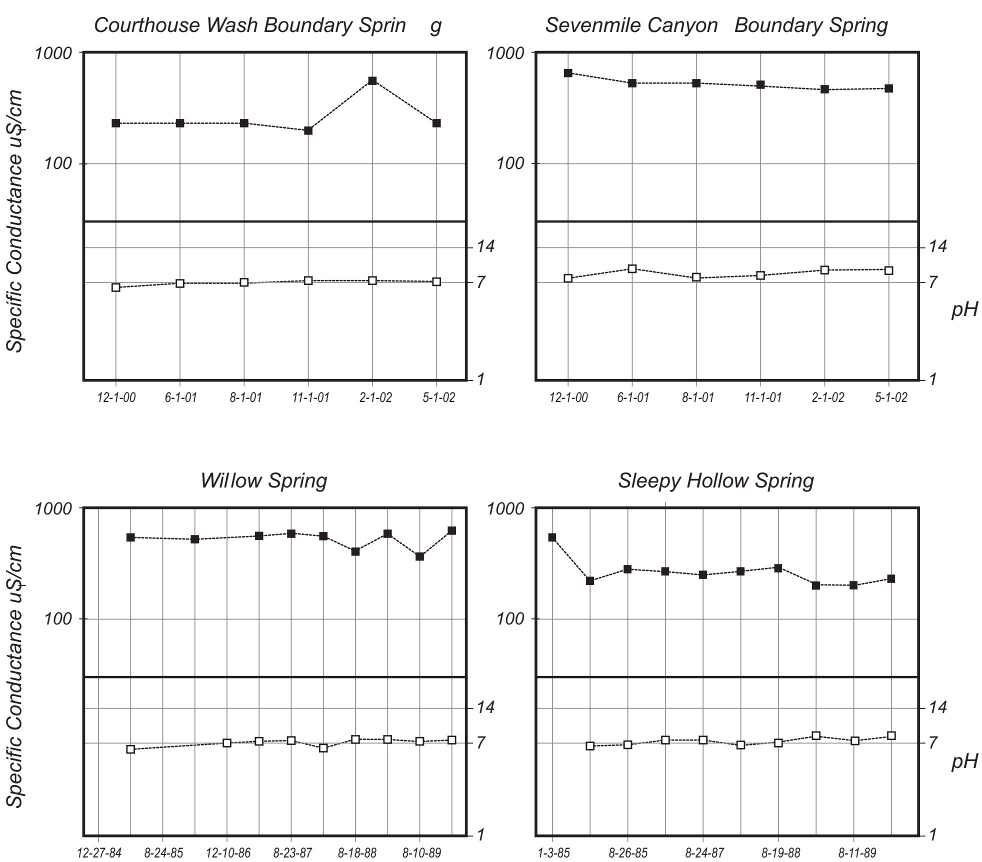



***Figure 15.*** *Specific conductance and pH of water from Courthouse Wash Boundary, Sevenmile Canyon Boundary, Willow, and Sleepy Hollow Springs.*

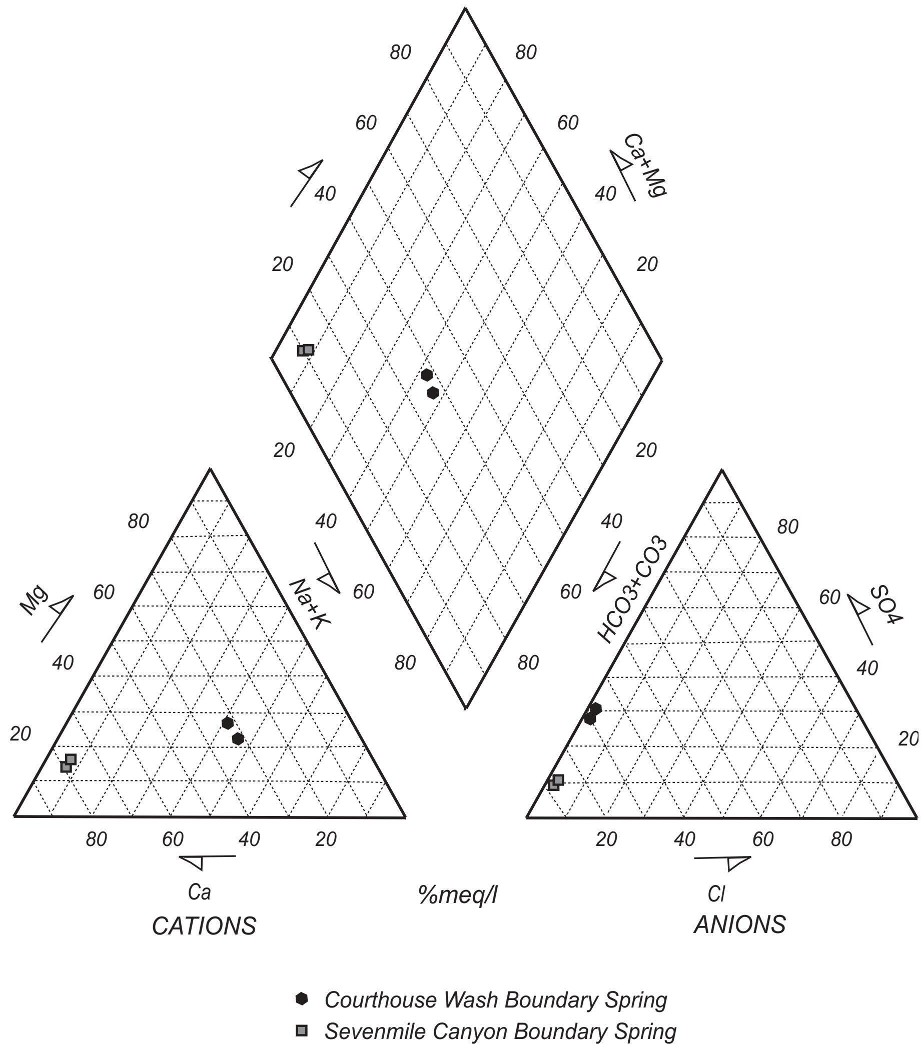



***Figure 16.*** *Trilinear diagram depicting geochemical analyses of water samples from Courthouse Wash Boundary Spring and Sevenmile Canyon Boundary Spring.*

with oxidizable materials encountered along its flow path. Based on temperature data, the initial concentration of dissolved oxygen in recharge water for the study area is between 8 and 11 mg/L. Comparison of estimated initial oxygen concentration with values measured at the springs in the study area reveals the fraction of dissolved oxygen retained during flow from recharge area to discharge area. Oxygen consumption in the aquifer depends on the aquifer lithology, especially the occurrence of pyrite and other oxygen-consuming minerals, the availability of organic compounds, and nutrients.

Based on its relatively high dissolved oxygen content, water from Courthouse Wash Boundary and Sevenmile Canyon Boundary Springs probably has limited contact with, and relatively fast flow through, the Moab Member aquifer. This conclusion is supported by the fact that the spring water shows minor variation in chemistry with time. Variations in spring-water temperature mimic seasonal changes observed at weather stations in the study area, confirming that the springs are part of a shallow flow system. We presently do not have sufficient data to estimate residence time of the spring water within the aquifer. Results from a sample submitted for tritium analysis were inconclusive.

## GEOLOGIC CONTROLS ON GROUND-WATER AND SPRING FLOW

### Stratigraphic Controls

As noted above, all springs and seeps in the study area except Courthouse Wash Boundary Spring and an unnamed spring in the northern group issue primarily from the unconformity between the Moab Member of the Curtis Formation and the Slick Rock Member of the Entrada Sandstone, and secondarily from cross-bed truncation planes in the lower 25 feet (8 m) of the Moab Member (figure 12). The same is true in Courthouse Wash and its side alcoves for about 2 miles (3 km) southeast of the study-area boundary, and for Willow Spring in Arches National Park about 1.5 miles (2.5 km) northeast of Courthouse Wash Boundary Spring (figures 3 and 7; plate 1).

The interformational contact and cross-bed truncation planes accommodate ground-water flow because they localize joints parallel to their surfaces. Gradual dissolution and removal of calcite cement has widened the apertures of these joints, further localizing ground-water flow (Doelling, 1988; Blanchard, 1990). Ground water does not flow downward into the Slick Rock Member because its upper surface is lined with fine-grained, impermeable, white mineral deposits derived from the ground water, preventing flow across the lower joint surface (Blanchard, 1990). The Slick Rock Member may also have lower hydraulic conductivity than the Moab Member due to finer grain size, poorer sorting, and lower joint density.

Water also seeps from joints in Willow Spring wash just above its intersection with Courthouse Wash (figure 17). These seeps form a pool at the mouth of Willow Spring wash, and water from this pool flows through unconsolidated deposits of a small alluvial fan at the wash mouth and discharges into Courthouse Wash.

At its point of origin, Courthouse Wash Boundary Spring issues from joints and cross-bed surfaces at the top of the Moab Member of the Curtis Formation (figure 2A). The intersection of Courthouse Wash with the contact between the Summerville Formation and the Moab Member determines the location of Courthouse Wash Boundary Spring (plate 1). Ground water in the Moab Member is likely confined upstream (northwest) of this point.

## Structural Controls

### Folds

Understanding the subsurface geometry of the Moab Member-Slick Rock Member contact is crucial to delineating the recharge areas of Courthouse Wash and Sevenmile Canyon Boundary Springs, because this contact strongly influences regional ground-water flow feeding these springs. Using available well and surface data and previously published cross sections (Doelling and Morgan, 2000), we constructed new geologic cross sections (plate 2) and a structure-contour map of the base of the Moab Member of the Curtis Formation (plate 3) to illustrate the subsurface structure in the Courthouse Wash–lower Sevenmile Canyon area. These diagrams show that the Courthouse syncline is an open fold with gently dipping limbs and a broad, poorly defined hinge zone that plunges gently northwest.

In the southwest limb of the Courthouse syncline near Sevenmile Canyon Boundary Spring, the base of the Moab Member forms a gentle, dome-basin structure with northwest-trending axes (plate 3). Evidence for this structure includes the elevation of the contact exposed in Sevenmile Canyon, and the log of a nearby petroleum-exploration well (well G, table A.1); its shape is otherwise not well constrained. These folds likely formed by local flow of salt in the underlying Paradox Formation. Some of the irregularity of the contours in this area may be due in part to variations in the stratigraphic thickness of the Moab Member.

The hanging wall of the Moab fault is deformed by a fault-parallel syncline-anticline pair (figure 7; plate 1; cross sections B-B′, D-D′, and E-E′, plate 2). The anticline probably represents the unbreached northwest continuation of the Moab salt anticline (Doelling, 1988; Foxford and others, 1996). The syncline may have formed from a combination of dissolution-related collapse of underlying units (Doelling, 1988) and displacement on the Moab fault (Foxford and others, 1996).

### Fractures

**Introduction:** Fractures are planar to gently curved mechanical discontinuities in rock, including joints, deformation bands, and faults. It is important to distinguish these fracture types in any hydrogeologic study of fractured bedrock because they influence ground-water flow in different ways.

Joints are simple breaks that form when the rock mass splits into two parts without relative motion on either side of the break. The flow rate of ground water through joints is significantly greater than through the rock matrix, although joints have a much lower capacity for storage. Joints can significantly affect the magnitude and direction of ground-water flow in bedrock aquifers, especially if a predominant, well-

***Figure 17.*** *Ground water seeping from joints in the Moab Member of the Curtis Formation in Willow Spring wash, about 300 feet (91 m) east of its confluence with Courthouse Wash. Channel bottom is about 3 feet across.*

connected set exists (Ritzi and Andolsek, 1992; Zhang and others, 1996). For example, laboratory measurements on unfractured sample cores of Navajo Sandstone from central Washington County in southwestern Utah yielded an average hydraulic conductivity of 2.1 feet per day (0.6 m/d), whereas well tests yielded hydraulic conductivities of 3.4 to 6.1 feet per day (1-1.9 m/d) (Cordova, 1978). The higher hydraulic conductivity values recorded by the field data are due primarily to joints (Cordova, 1978). A recent aquifer test in the Navajo Sandstone indicated a hydraulic conductivity anisotropy factor of about 24:1 to the northwest, parallel to a set of numerous, long, well-connected joints (Heilweil and others, 2000).

Deformation bands accommodate displacements in porous rock on the order of a few millimeters to a few centimeters, forming thin, resistant, anastomosing bands (Aydin and Johnson, 1978; Antonellini and Aydin, 1994). Deformation bands impede ground-water flow across their planes due to their very fine-grained, poorly sorted internal fabric derived from crushing of the host-rock grains (Antonellini and Aydin, 1994).

Faults may accommodate displacement of tenths of inches to thousands of feet (millimeters to kilometers) between adjacent rock masses, forming a variety of structures in the process. The nature of the material formed in the central part (core) of a fault, which accommodates the relative displacement, varies with the composition of the adjacent rocks and the magnitude of displacement (Caine and others, 1996). Fault-core material derived from clay-bearing rocks such as shale or arkosic sandstone is very fine grained, soft, and scaly, whereas fault-core material derived from quartzite or limestone varies from fine-grained gouge to coarse breccia but lacks clay. Retardation of ground-water flow perpendicular to a fault plane increases with increasing clay content, decreasing grain size, and decreasing sorting of the fault-core material (Caine and others, 1996). Dense jointing in the rock mass adjacent to a fault plane, best developed in well-cemented, clay-poor rocks, enhances ground-water flow parallel to the fault plane (Caine and others, 1996).

**Joints:** To characterize jointing in the Moab Member in the Courthouse Wash-lower Sevenmile Canyon area, we performed reconnaissance field evaluation of joints throughout the area and quantitative analysis at three sites. The quantitative approach is known as the scanline technique (La Pointe and Hudson, 1985), in which fracture properties are recorded along two perpendicular sampling traverses.

Scanline analyses of joints at three sample sites show that the northwest-striking joint set has the greatest average length, and that northeast-striking joints are typically more closely spaced and more abundant (table 9; figure 18). At sites S1 and S2, the northwest-striking joint set formed first, and one or both ends of the northeast-striking set terminate at northwest-striking joints. This geometry results in good connectivity between the two joint sets. These relations are reversed at scanline site S3 (table 9; figure 18c) and at several other places in the study area.

**Deformation bands:** Deformation bands are ubiquitous along the Moab fault (see next section), and are common but widely spaced within about 1 mile (1.6 km) of the fault trace. The fault crossing the head of lower Sevenmile Canyon (plate 1) is a tightly spaced cluster of deformation bands, termed a deformation-band zone (Antonellini and Aydin, 1994). Isolated deformation bands are common near this fault, and gradually decrease in abundance to the east. Deformation bands typically form conjugate sets, with the set parallel to the Moab fault most abundant (figure 19).

**Moab fault:** In the Courthouse Wash-lower Sevenmile Canyon area, the Moab fault strikes northwest, dips 50-75° northeast, and juxtaposes the Salt Wash Member of the Morrison Formation in its hanging wall against the lower part of the Cutler Formation in its footwall (figure 20A; plate 1; cross sections B-B′ and D-D′, plate 2). The maximum stratigraphic separation along this section of the Moab fault is about 3,100 feet (945 m) (Doelling, 1988; Doelling and Morgan, 2000, their cross section B-B′). The Moab Member of the Curtis Formation is exposed in the hanging wall of the

***Table 9.*** *Scanline data for sample sites in the study area. See text for discussion.*

| Sample Number and Location[1] | Joint Set | Average Orientation[2] | Average Length in meters (number of observations) | Average Spacing in meters (number of observations) |
|---|---|---|---|---|
| **S1** | Northwest | 331, 76 | 4.7 + 1.9 (11) | 3.5 + 1.2 (10) |
| Courthouse Wash | Northeast | 73, 80 | 3.3 (2) | 4.4 (1) |
| Boundary Spring | Cross-bed Surfaces | 322, 12 | 1.6 + 0.2 (15) | 0.04 + 0.01 (12) |
| **S2** | Northwest | 311, 82 | 19 + 7.2 (5) | 11.7 + 2.4 (4) |
| Cedar Point | Northeast | 195, 81 | 9.7 + 2.6 (10) | 4.5 + 1.5 (9) |
| **S3** | Northwest | 319, 81 | 8.3 + 4.8 (5) | 8.7 + 5.6 (4) |
| Above Sevenmile Canyon | Northeast | 234, 76 | 8.5 + 3.3 (6) | 7.4 + 2.2 (5) |
| Boundary Spring | Cross-bed Surfaces | 290, 10 | 9.4 + 3.3 (8) | 0.4 + 0.1 (7) |
| Combined Data | Northwest | 323, 79 | 9.0 + 2.5 (21) | 6.5 + 1.6 (18) |
| | Northeast | 197, 79 | 8.6 + 1.8 (18) | 5.7 + 1.2 (14) |
| | Cross-bed Surfaces | 298, 10 | 4.3 + 1.2 (23) | 0.2 + 0.05 (19) |

Notes:
[1] See plate 1 for locations.
[2] Strike and dip of joints is given in right-hand-rule/azimuth notation. In azimuth notation, the compass is divided into 360 degrees: 0° and 360° are both North, 90° is East, 180° is South, and 270° is West. In right-hand rule notation, the strike is reported as the compass reading when looking in the strike direction such that bedding dips down to the right. The strike of a planar feature is the direction of the line of intersection between a horizontal plane and the feature. The dip of a planar feature is the acute angle between the feature and a horizontal plane, measured in a vertical plane with values from 0 to 90 degrees increasing downward.

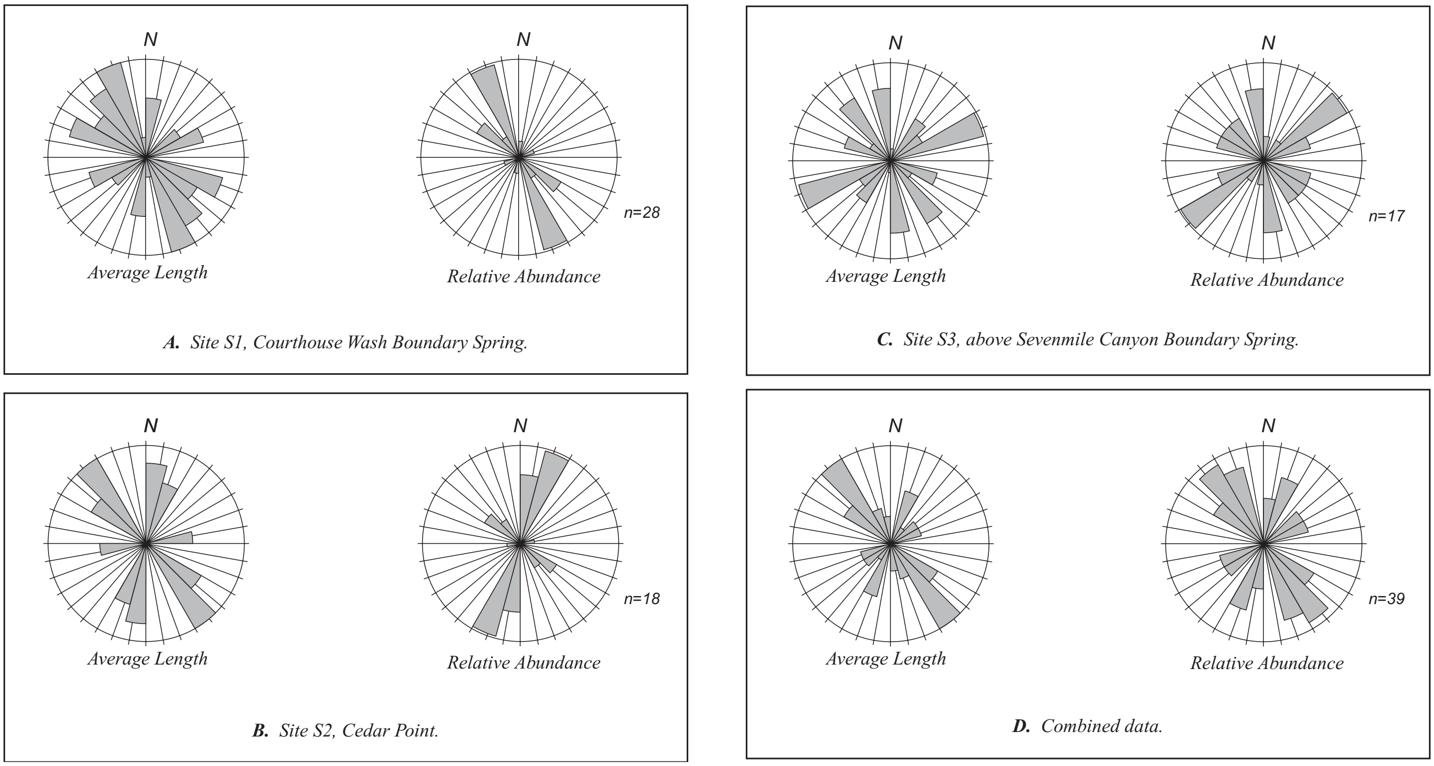



***Figure 18.*** *Equal-area "rose" histograms illustrating average lengths and orientations of joints at the sample sites listed in table 9. Plate 1 shows the sample sites, all of which are on the Moab Member of the Curtis Formation. In these plots, joints are grouped by strike into 15-degree sectors (tick lines are in 10-degree intervals). Adjacent to the circles, n = number of joints. The plots are "bi-directional" – the rose petals include data for joints having the same strike range but opposite dip directions. Average length plots – rose petal length is proportional to the average length of joints in each sector; values are in table 9. Relative abundance plots – rose petal lengths are proportional to abundance normalized to total number of joints measured at the sample site.*

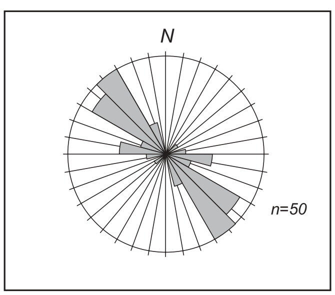



***Figure 19.*** *Equal-area "rose" histogram illustrating the orientations of deformation bands more than about 100 feet (30 m) east of the Moab fault, including the deformation-band zone crossing the head of lower Sevenmile Canyon shown as a fault on plate 1. The data are from individual sites throughout the study area, and the "rose-petal" lengths only qualitatively reflect the relative abundances of deformation bands in each orientation sector. See figure 18 caption and table 9 for explanation of rose histograms.*

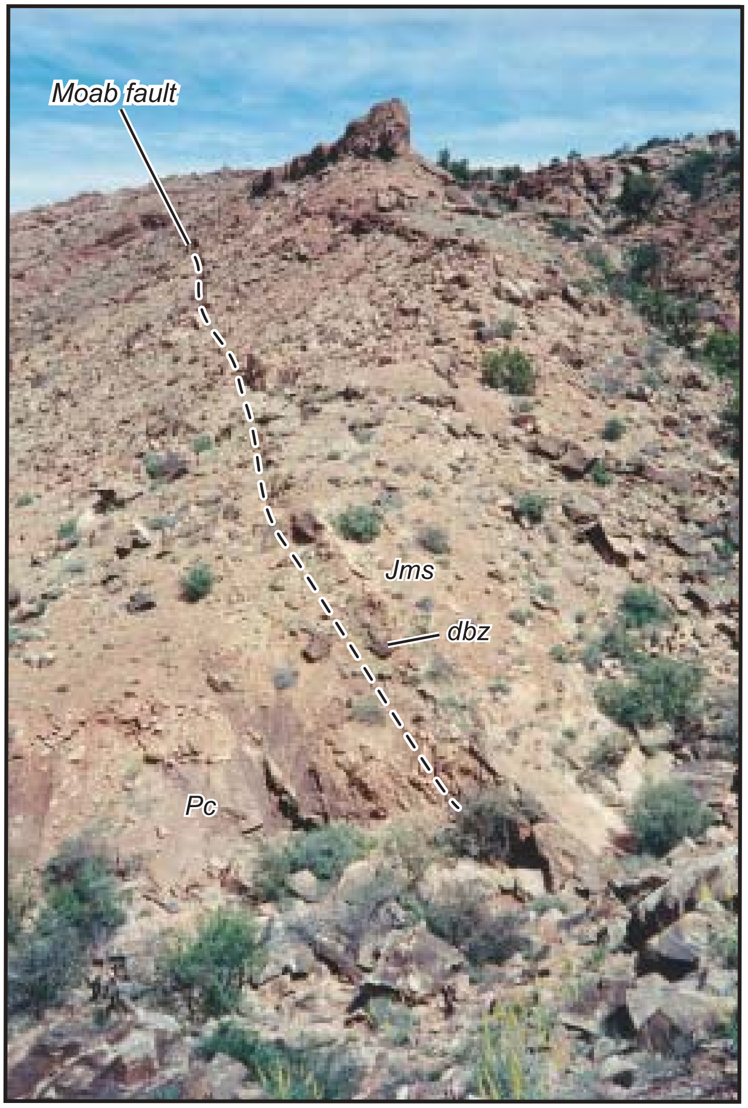
Moab fault southeast of the study area (figure 9), and the Cedar Mountain and Dakota Formations in the hanging wall are juxtaposed against Jurassic to Cretaceous formations in the footwall in the northwest part of the study area (figure 7).

Fault-related fabrics in the Moab fault core include deformation-band zones, discrete slip surfaces, scaly foliation, silica-cemented fault breccia, and clay-rich gouge (figure 20) (Foxford and others, 1996). Deformation-band zones vary from about 1.5 to 5 feet (0.5-1.5 m) thick, and are composed of closely spaced, anastomosing deformation bands (figures 20A, 20B, and 21A). The deformation-band zones are extremely hard due to pervasive silica cementation (figures 20A and 20B). Most slip surfaces are slickensided, with or without striae (figures 20A, 20B, and 20C), and strike parallel to the Moab fault plane although a variety of orientations are present (figure 21B).

Very hard, silica-cemented fault breccia derived from the Wingate Sandstone is present in the Moab fault core northwest of U.S. Highway 191 (figures 20C and 20D). Clay-rich gouge forms a 1-foot-thick (30.5 cm), light-colored band between hanging-wall and footwall rocks in a spectacular road cut along the old Moab Highway, just south of the southern study-area boundary (figure 20E). The scaly-foliated fabric in the Cutler Formation (figures 20A and 20E) varies from about 1 to 10 feet (0.3-3 m) in thickness.

Deformation within about 100 feet (30 m) of the Moab fault plane, in the region known as the damage zone (Caine and others, 1996), is intense and includes deformation bands, discrete slip surfaces, and joints (figures 9 and 20E). These features are best exposed in hanging-wall rocks, and their density decreases steadily away from the main fault plane. Deformation bands in the Moab fault damage zone include a more abundant primary set parallel to the main fault trace and a secondary set forming a conjugate pair with the primary set (figure 21C). Joints in the Moab fault damage zone form two distinct orientation sets striking north-northwest and northeast (figure 21D). The strikes of these joint sets are rotated about 20 degrees clockwise from the strikes of the two main joint sets far from the Moab fault (compare figures 18D and 21D), probably due to local rotation of the regional stress field near the Moab fault.

A




B


***Figure 20.*** *Views of the Moab fault. A. View to the northwest, showing r esistant deformation-band zone (dbz) in sandstone of the Salt W ash Member of the Morrison Formation (Jms), and scaly foliation cut by slip surfaces in the Cutler Formation (Pc). The deformation-band zone likely forms a barrier to cr oss-fault gr ound-water flow in the subsurface. View is about one mile (1.6 km) southeast of the southern study-area boundary. B. View to the northeast of the Moab fault juxtaposing sandstone of the Cedar Mountain Formation (Kcm) in the hanging wall against mudstone of the Chinle Formation (T̶Rc) in the footwall. The Moab fault core consists of a 1-foot-thick (0.3 m) deformation-band zone (dbz) in Cedar Mountain sandstone and scaly foliation in Cedar Mountain and Chinle mudstones. The sandstone-mudstone contact is a smooth, slickensided slip surface. Hammer is 11 inches (28 cm) long.*

C


D

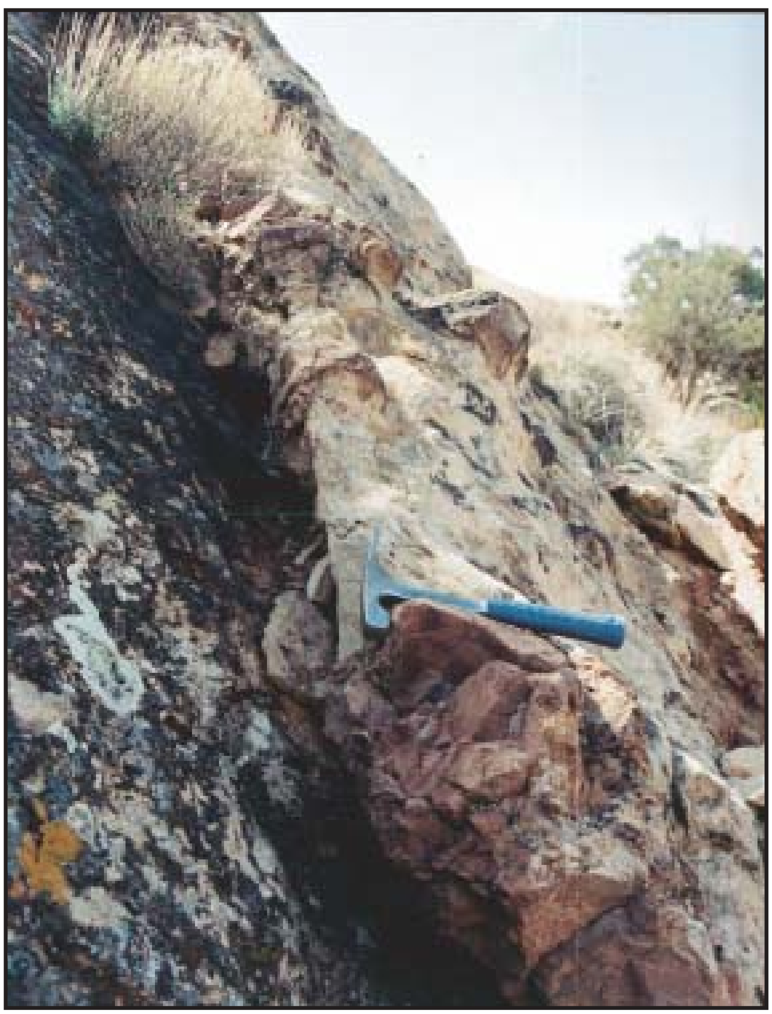


***Figure 20 (continued).*** *C. View to the southwest, showing sandstone and mudstone of the Dakota Sandstone (Kd) in the hanging wall juxtaposed against the W ingate Sandstone (Jw) in the footwall. The rock hammer rests on a silica-cemented breccia zone in the fault cor e, bounded by a slickenside surface (smooth surface) in the Wingate Sandstone. This cemented br eccia zone likely forms a barrier to ground-water flow in the subsurface. Hammer (cir cled) is 11 inches (28 cm) long. D. Closer view of the silica-cemented fault br eccia shown in C. Hammer is 11 inches (28 cm) long.*

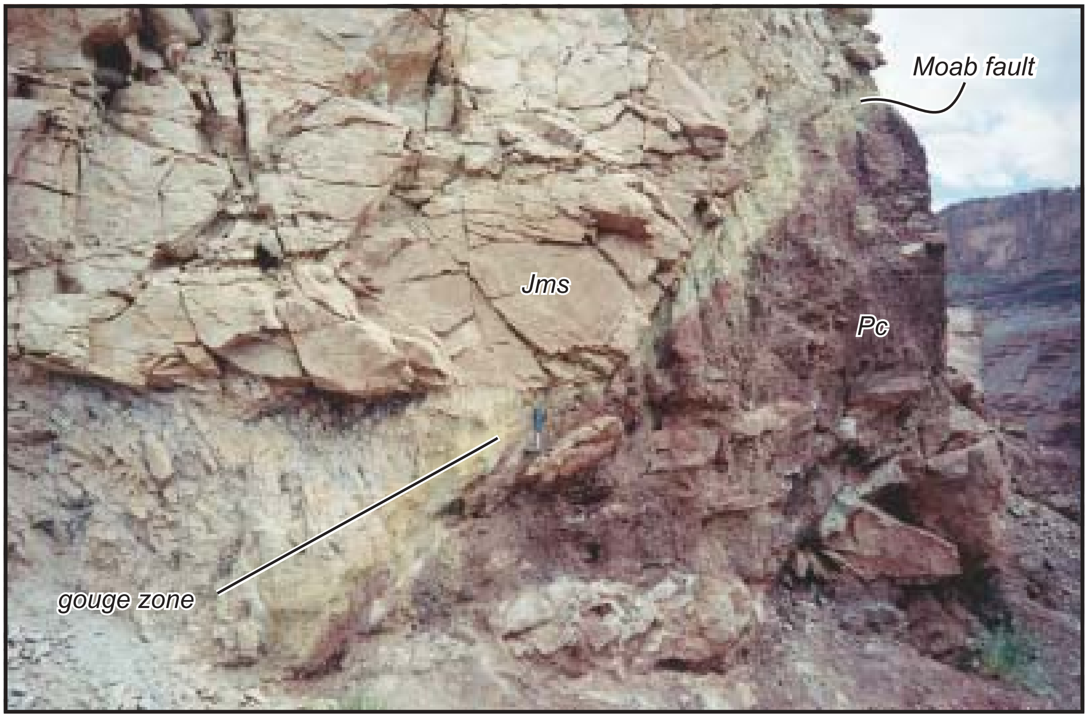



*Figure 20 (continued).* *E. View to the southeast of a road cut along the old Moab Highway, near the southern study-area boundary. Sandstone of the Salt Wash Member of the Morrison Formation (Jms) in the hanging wall is densely jointed, and bedding in arkosic sandstone and mudstone of the Cutler Formation (Pc) in the footwall is highly disrupted and cut by slip surfaces. The fault core is composed of a 1-foot-thick (0.3 m), clay-rich gouge zone (pale band just above hammer) that likely forms a barrier to cross-fault ground-water flow in the subsurface. Hammer is 11 inches (28 cm) long.*

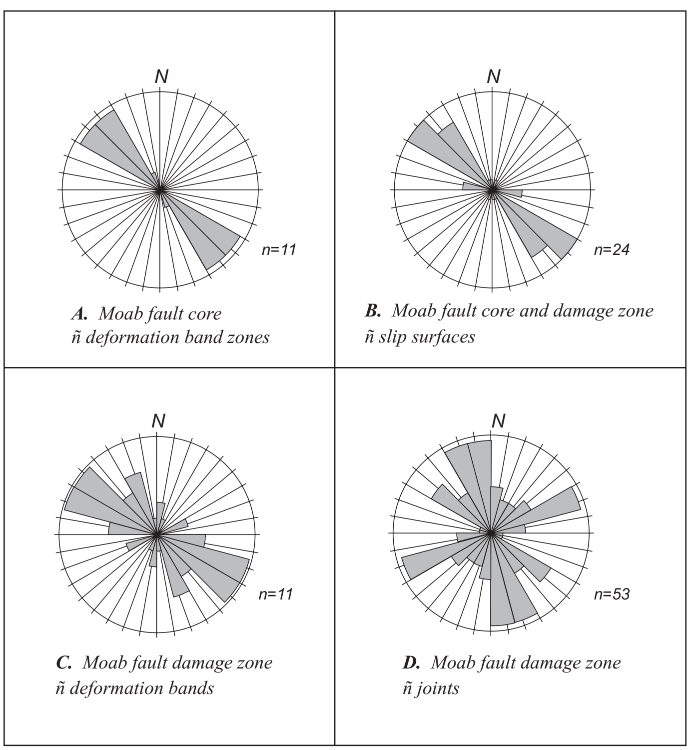



*Figure 21. Equal-area "rose" histograms illustrating the orientations of structural elements in and adjacent to the Moab fault core. The data are from individual sites throughout the study area, and the "rose-petal" lengths only qualitatively reflect the relative abundances of deformation bands in each orientation sector. See figure 18 and table 9 captions for further explanation of rose histograms.*

## Discussion – Effects on Ground-Water Flow

The Moab Member-Slick Rock Member contact and the Courthouse syncline control regional flow patterns in the ground-water system that feeds the Courthouse-Sevenmile spring system. Recharge from precipitation flows downward through joints and through the matrix of the Moab Member to its lower boundary with the Slick Rock Member. Ground water flows along the Moab Member-Slick Rock Member contact toward the syncline axis. Ground water in the northeast limb of the Courthouse syncline flows to the southwest, and flow in the southwest limb is to the northeast. The ground water discharges to Courthouse Wash in the hinge zone of the Courthouse syncline.

Courthouse Wash closely follows the axial trace of the Courthouse syncline, suggesting a genetic relationship. The fold geometry has likely focused surface and ground-water flow to the hinge area, as described above, for thousands to millions of years, causing greater erosion along the hinge and localization of the stream (Doelling, 1988). This probably occurred after erosion removed the Morrison and Summerville Formations, allowing the Moab Member of the Curtis Formation to receive significant recharge from precipitation.

The small-scale dome-and-basin structure near Sevenmile Canyon Boundary Spring may locally affect ground-water flow in the Moab Member aquifer by diverting it around the small dome north of Sevenmile Canyon. These folds probably do not significantly affect the ground-water flow system supplying the Courthouse-Sevenmile spring system.

The northwest-striking joint set in the Moab Member of the Curtis Formation likely imparts a northwest-southeast anisotropy of unknown magnitude to ground-water flow, based on orientation, length, and spacing data presented above. In the unconfined part of the Moab Member aquifer, ground water flows primarily along the Moab Member-Slick Rock Member contact and cross-bedding truncation planes within the lower 25 feet (8 m) of the Moab Member. The effect of joints on flow in the unconfined Moab Member aquifer, therefore, is likely of secondary importance. Flow is distributed through the entire thickness of the confined part of the Moab Member aquifer, and the joints likely exert more control on the ground-water flow direction there.

Deformation-band zones, silicified fault breccia, clayey gouge, and foliated fault rock in the Moab fault core (figure 20) all likely retard ground-water flow perpendicular to the fault plane (Caine and others, 1996). The abrupt change in ground-water levels across the fault, described above, supports this inference. High joint density adjacent to the Moab fault (figures 9 and 20) likely enhances fault-parallel flow of ground water (Caine and others, 1996).

# DELINEATION OF RECHARGE AREAS

## Introduction

We delineated the parts of the Moab Member aquifer contributing recharge to the three spring groups within the Courthouse-Sevenmile spring system to better enable park officials to protect the quality and quantity of water issuing from the springs. Delineation of the recharge areas includes estimating the total area that contributes to spring flow and identifying the physical boundaries of the recharge areas. Our approach to this problem includes: (1) calculating recharge areas for Courthouse Wash Boundary Spring, Sevenmile Canyon Boundary Spring, Poison Ivy Spring, and Sleepy Hollow Spring; (2) expanding these initial estimates to incorporate flow from other springs in each of the three spring groups; and (3) delineating the recharge areas for Courthouse Wash Boundary Spring and the eastern and western spring groups, based on our conceptual model of recharge, flow, and discharge within the Moab Member aquifer.

## Recharge-Area Calculations

### Introduction

We used water-budget and catchment-area methods to estimate the land-surface areas contributing recharge to individual springs, and a volumetric travel-time method to estimate the aquifer area needed to supply the springs. The methods involve simple calculations that require little data, and do not incorporate the hydrogeologic complexities of the Courthouse-Sevenmile spring system. The water-budget and catchment-area methods do not predict the shape or location of the contributing area; these features must be estimated from the hydrogeologic setting of the springs.

The water-budget method provides a good estimate of the size of the area contributing recharge to springs and seeps that obtain water solely from infiltration of local precipitation. The catchment-area method uses a graph presented in Todd (1980, fig. 2.16, p. 49), which depicts the relationship between recharge area, annual recharge, and spring discharge. The volumetric travel-time method defines an aquifer area contributing to the spring, but not a land-surface recharge area in contrast to the other two methods. The aquifer area estimated from the travel-time method should be smaller than the land-surface recharge areas estimated from the water-budget and catchment-area methods, because only part of the water infiltrating to the aquifer actually discharges at the springs.

### Methods and Results

Table 10 summarizes flow data and related statistics for Courthouse Wash Boundary Spring, Sevenmile Canyon Boundary Spring, Sleepy Hollow Spring, and Poison Ivy Spring. We used the maximum discharge measured for each spring in our recharge-area calculations because: (1) precipi-

***Table 10.*** *Summary statistics for spring discharge data.*

| | Courthouse Wash Boundary Spring | Sevenmile Canyon Boundary Spring | Sleepy Hollow Spring | Poison Ivy Spring |
|---|---|---|---|---|
| Number of Measurements | 14 | 16 | 15 | 14 |
| Range (gpm) | 8.06 | 4.0 | 3.86 | 2.1 |
| Minimum (gpm) | 8.66 | 6.57 | 6.16 | 2.23 |
| Maximum (gpm) | 16.72 | 10.57 | 10.02 | 4.33 |
| Mean (gpm) | 12.79 | 8.23 | 7.83 | 3.36 |
| Standard Error | 0.59 | 0.25 | 0.25 | 0.16 |
| Median (gpm) | 13.12 | 8.26 | 7.87 | 3.51 |
| Standard Deviation | 2.27 | 1.01 | 1.07 | 0.62 |
| Variance | 5.13 | 1.03 | 1.14 | 0.39 |
| Kurtosis | -0.14 | 0.73 | -0.22 | -0.79 |
| Skewness | -0.41 | 0.52 | 0.17 | -0.39 |

tation in the study area from 1987 through 2001 was 60 to 85 percent of normal, probably strongly affecting discharge in the Courthouse-Sevenmile spring system, and (2) discharge measurements used to estimate spring recharge areas should be conservative in order to account for factors not included in the assumptions of the equations, and to provide maximum protection of discharge and water quality. The maximum flow value for Poison Ivy Spring was increased by 30 percent for use in the equations to account for the fact that a substantial amount of its discharge was not captured at the measuring point.

**Water-budget method:** The area contributing recharge to a shallow water-table aquifer, in most hydrogeologic settings, is related to spring discharge and local recharge rate. Assuming a steady-state water budget, the contributing area can be computed using the following equation (Bishop, 2001):

Eq. 1 $$A = \frac{Q}{R}$$

Where:

A is land-surface recharge area in square feet,

*Q* is spring discharge in cubic feet per year, and

*R* is ground-water recharge rate in feet per year.

Ground-water recharge of the Moab Member aquifer in the study area is about 0.5 inch per year (1 cm/yr).

Table 11 summarizes the results of the calculations. Courthouse Wash Boundary Spring requires a recharge area of about 1.05 square miles (2.7 $km^2$), Sevenmile Canyon Boundary Spring requires a recharge area of 0.67 square miles (1.7 $km^2$), Sleepy Hollow Spring requires a recharge area of 0.64 square miles (1.7 $km^2$), and Poison Ivy Spring requires a recharge area of 0.35 square miles (0.9 $km^2$).

The water-budget equation is equally sensitive to uncertainties in spring discharge and aquifer recharge. We estimated the probable ranges of these parameters for Courthouse Wash Boundary Spring, based on values obtained or estimated during the study to provide an example of the sensitivity of the recharge-area estimates (table 12). Within the estimated ranges of hydrologic parameters for Courthouse Wash Boundary Spring, the recharge area can vary by over four times in size (comparing results using maximum spring discharge and minimum recharge rate to results using minimum spring discharge and maximum recharge rate). The recharge area calculation is slightly more sensitive to the range in recharge rate than the range in spring discharge (table 12).

**Catchment-area method:** We calculated hypothetical catchment areas for the springs, based on recharge and discharge estimates, using the graphical method of Todd (1980, p. 49). These recharge-area estimates are highly sensitive to the value of recharge rate, which is not confidently known for the study area. Thus, the results are subject to significant uncertainty. Courthouse Wash Boundary Spring requires a recharge area of about 1.2 square miles (3.1 $km^2$), Sevenmile Canyon Boundary Spring requires a recharge area of 0.73 square miles (1.9 $km^2$), Sleepy Hollow Spring requires a recharge area of 0.66 square miles (1.7 $km^2$), and Poison Ivy Spring requires a recharge area of 0.34 square miles (0.9 $km^2$) (table 11).

**Travel-time method:** This method estimates the top-surface area of the volume of an aquifer contributing to spring discharge (Bishop, 2001). For a spring flowing at a rate Q over a time period $t_i$ the total volume of water discharged is $Qt_i$. The method assumes that a half-cylinder volume of aquifer focused at the spring supplies the spring flow. This half cylinder has a radius r, thickness b, and effective porosity θ, and the total volume of water contained therein is $1/2(\theta b \pi r^2)$. Assuming that there are no long-term storage changes in the aquifer, the water recharging the aquifer must balance the amount of water discharging at the spring. Equating these two volumes of water and solving for area yields the following equation (Bishop, 2001):

Eq. 2 $$A = \frac{2Qt_i}{b\theta}$$

Where:

*A* is the aquifer area contributing to spring flow, in square feet,

*Q* is spring discharge in cubic feet per year,

$t_i$ is time of travel in years,

*b* is average aquifer thickness in feet, and

$\theta$ is effective porosity (dimensionless).

The hydrologic parameters used in this calculation are based on evaluation of data for the Moab Member aquifer. Geochemical evaluation of the springs suggests that the water has been in the ground for a relatively short time, so we used a travel time of 50 years. Values of effective porosity and average saturated thickness were estimated as 0.2 and 80 feet (24 m), respectively, based on data in Jobin (1962), Weigel (1987), and Freethey and Cordy (1991).

The contributing areas computed using a 50-year travel time are 0.26 square mile (0.7 $km^2$) for Courthouse Wash Boundary Spring, 0.17 square mile (0.4 $km^2$) for Sevenmile Canyon Boundary Spring, 0.16 square mile (0.4 $km^2$) for Sleepy Hollow Spring, and 0.09 square mile (0.2 $km^2$) for Poison Ivy Spring (table 11). These aquifer top-surface areas are about 25 percent of the land-surface areas estimated from the water-budget and catchment-area methods for the springs.

The travel-time equation is sensitive to uncertainties in spring discharge; time of travel, which was arbitrarily picked as 50 years; average aquifer thickness; and effective porosity. The recharge area for the springs may vary by about four times in size, and the calculation is most sensitive to uncertainties in aquifer thickness as illustrated by the example of Courthouse Wash Boundary Spring (table 13).

## Discussion

These recharge-area calculations provide reasonable and consistent estimates of the land surface area and aquifer area supporting flow to the four springs (table 11). We believe that the water-budget method provides the best estimates for the western and eastern spring groups, because it assumes that local precipitation and snowmelt are the sole source of recharge, consistent with the geologic boundary conditions and geochemical data presented above. For Courthouse Wash Boundary Spring, the water-budget and catchment-area methods may be equally applicable because the spring

***Table 11**. Comparison of recharge-area estimates from three alternative methods. See text for explanation of methods.*

| Spring | Discharge (gpm) | Recharge Area mi² (km²) Water-Budget Method[1] | Recharge Area mi² (km²) Catchment-Area Method[2] | Aquifer mi² (km²) Travel-Time Method[3] |
|---|---|---|---|---|
| Courthouse Wash Boundary | 16.72 | 1.05 (2.7) | 1.2 (3.1) | 0.26 (0.7) |
| Sevenmile Canyon Boundary | 10.57 | 0.67 (1.7) | 0.73 (1.9) | 0.17 (0.4) |
| Sleepy Hollow | 10.02 | 0.64 (1.7) | 0.66 (1.7) | 0.16 (0.4) |
| Poison Ivy | 5.63 | 0.35 (0.9) | 0.34 (0.9) | 0.09 (0.2) |

Notes: [1]This report, equation 1.
[2] Todd (1980, p. 49).
[3] This report, equation 2.

***Table 12**. Sensitivity analysis of water-budget calculation for Courthouse Wash Boundary Spring. Input values are in shaded cells; uncertainties in italic font are in unshaded cells.*

| Spring Discharge (gpm) | Recharge Rate (in/yr) | | |
|---|---|---|---|
| | 0.27 | 0.46 | 0.63 |
| 16.72 | *1.9* | *1.05* | *0.8* |
| 8.66 | *0.97* | *0.55* | *0.42* |

likely receives some recharge from the confined Moab Member aquifer to the west and north. The two methods yield comparable estimates (table 11).

Our estimates of the recharge areas required to support flow in the eastern and western spring groups are less than the outcrop areas of the Moab Member aquifer available to the springs, consistent with geochemical and temperature data indicating that ground water in this flow system has a relatively short residence time and interacts only with the calcite cement of the Moab Member.

## Delineation of Recharge Areas

As discussed above, Courthouse Wash Boundary Spring, Sevenmile Canyon Boundary Spring, Sleepy Hollow Spring, and Poison Ivy Spring are part of a larger spring system fed by the geographically and hydrologically partitioned, shallow Moab Member aquifer. To estimate the total land-surface areas contributing to the western and eastern spring groups, we made rough estimates of the discharge from unmeasured springs and seeps, and estimated their recharge areas using the ratios of flow to recharge area for the individual springs calculated above. We also delineated the recharge area for Courthouse Wash Boundary Spring based on the recharge-area estimates described above. The water-budget and catchment-area methods provide estimates of the land-surface area contributing recharge to the springs, but no quantitative information concerning the shapes of these areas. Estimating the shapes and locations of the recharge areas requires inferences based on the local hydrogeologic regime.

The maximum possible extents of the recharge-area boundaries upgradient of the springs are defined by ground-water flow divides where subsurface flow diverges to supply different spring systems, the physical boundaries of the Moab Member aquifer, and the canyons that incise and hydrologically partition the aquifer. The areas estimated from the water-budget and catchment-area methods must fit within these physical limits. The shape of each contributing area is drawn to be consistent with a sloping, anisotropic, non-uniform water table that reflects topography and extends toward inferred topographic and surface-water divides, which we assume coincide with ground-water divides.

***Table 13.** Sensitivity analysis of travel-time calculation for Courthouse Wash Boundary Spring. Input values are in shaded cells; uncertainties in italic font are in unshaded cells.*

| Spring Discharge | Aquifer Thickness (feet) | | | Effective Porosity | | |
|---|---|---|---|---|---|---|
| (gpm) | 120 | 80 | 40 | 0.25 | 0.2 | 0.15 |
| 16.72 | *0.17* | *0.26* | *0.09* | *0.21* | *0.26* | *0.35* |
| 8.66 | *0.52* | *0.14* | *0.27* | *0.11* | *0.14* | *0.15* |

The eastern spring group is recharged by infiltration of precipitation and snowmelt on Moab Member outcrop east of Courthouse Wash, and includes Sleep Hollow Spring, for which we estimate a land surface recharge area of 0.64 square mile (1.7 $km^2$) (table 13). Based on qualitative comparison of discharge, we estimate that the other springs and seeps along the eastern wall of Courthouse Wash collectively require a recharge area of about 0.4 square mile (0.9 $km^2$). The entire eastern spring group, therefore, requires a recharge area of about 1.04 square miles (2.7 $km^2$). Figure 22 shows our estimate of the land-surface area contributing to discharge in the eastern spring group and flow lines to the springs, based the analyses described herein. Sufficient outcrop area of the Moab Member exists to supply the eastern spring group, and flow is down the dip of the southeastern limb of the Courthouse syncline. Courthouse Wash truncates the contributing area on the west.

The western spring group is recharged by infiltration of precipitation and snowmelt on Moab Member outcrop south of Sevenmile Canyon and west of Courthouse Wash, and includes Sevenmile Canyon Boundary Spring and Poison Ivy Spring. The combined estimated recharge area for these two springs is about 1.0 square mile (2.6 $km^2$). A second spring in the same alcove as Poison Ivy Spring has approximately the same discharge, and several other seeps and minor springs discharge from alcoves in the west wall of Courthouse Wash. We estimate that these springs and seeps collectively require a recharge area of about 0.5 square mile (1.3 $km^2$). The western spring group, therefore, requires recharge on about 1.5 square miles (3.9 $km^2$) of land surface. Figure 22 illustrates our best estimate of the land-surface area that contributes to the discharge of the western spring group. The outcrop area of the Moab Member aquifer south of Sevenmile Canyon and upgradient from the western group of springs is about 2.0 square miles (5 $km^2$), so sufficient outcrop of the Moab Member aquifer exists to supply the observed discharge to the western spring group. Sevenmile Canyon truncates the contributing area on the north and Courthouse Wash truncates the contributing area on the east.

Courthouse Wash Boundary Spring receives recharge from (1) infiltration of precipitation and snowmelt on Moab Member outcrop northeast of the spring, (2) flow from the confined Moab Member aquifer west and north of the spring, and (3) infiltration of precipitation and snowmelt on alluvium in Courthouse Wash. Although we cannot quantitatively estimate their proportions, we list these sources in their relative order of importance as inferred from our geochemical data. Courthouse Wash Boundary Spring, therefore, has multiple sources of recharge including the confined Moab Member aquifer underlying private and state-owned land to the west and north.

Figure 22 illustrates schematically the recharge area and flow lines for Courthouse Wash Boundary Spring, based on an assumption of radial flow to the spring modified by the dips of both limbs of the Courthouse syncline and constrained by the position of Courthouse Wash and Sevenmile Canyon. Where this recharge area overlies Moab Member outcrop, recharge is by infiltration of precipitation and snowmelt on bedrock and through thin surficial deposits, and the unconfined Moab Member aquifer contributes to the discharge of Courthouse Wash Boundary Spring. Where the recharge area overlies outcrop of Morrison and Summerville Formations, the confined Moab Member aquifer contributes flow to Courthouse Wash Boundary Spring. Figure 22 shows roughly equal contributions from these two sources, but we have not quantified this assumption. We do not have additional hydrogeologic data to better constrain this recharge area.

## Conceptual Model of Flow in the Moab Member Aquifer

Based on the data, observations, calculations, and interpretations presented above, we characterize the hydrologic system including the Moab Member aquifer and Courthouse-Sevenmile spring system as follows.

The Moab Member aquifer is unconfined where the Moab Member of the Curtis Formation is exposed, and is confined north and west of the Courthouse-Sevenmile spring system where it underlies the Summerville and Morrison Formations. Pressure conditions in the Moab Member aquifer are likely gradational between confined and unconfined where it is buried beneath less than about 25 feet (8 m) of overlying deposits. Water levels in wells completed in the confined Moab Member aquifer rise above the top of the aquifer. The entire thickness of the aquifer, therefore, is saturated and the water is under pressure. In contrast, the potentiometric surface is generally below the top of the unconfined Moab Member. In these areas only part of the Moab Member is saturated. The potentiometric surface emerges near the top of the Moab Member at the Courthouse Wash Boundary Spring, which is about 6 feet (2 m) below the top of the formation.

Courthouse Wash Boundary Spring issues from the top of the Moab Member aquifer and likely receives contributions from both the confined part of the aquifer to the west and north, and the unconfined part of the aquifer to the east. Ground-water levels in wells screened in the Moab Member of the Curtis Formation about 2 miles (3.2 km) west of Courthouse Wash Boundary Spring are about 20 to 90 feet (6-27 m) higher than the spring. The structure-contour map (plate 3) indicates that the Moab Member is physically continuous between the two areas. Ground water likely flows from the area of the wells toward Courthouse Wash Boundary Spring and the rest of the northern spring group, and the two areas are likely in direct hydrologic communication. Some ground water may move along the Moab fault and recharge the confined part of the Moab Member aquifer. This ground water probably comes from the north and accounts for the higher pressures in the area.

Recharge to the unconfined Moab Member aquifer occurs by infiltration of precipitation and snowmelt on Moab Member outcrop, and through thin surficial deposits covering outcrops. The geochemistry of spring water and the fine-grained nature of the Morrison and Summerville Formations suggests that infiltration through these units is relatively less important. Ground water collects at the base of the Moab Member and flows along it, due to the high transmissivity of the lower contact of the Moab Member and to the presence of impermeable deposits on the upper surface of the underlying Slick Rock Member.

Flow patterns toward the eastern and western spring groups generally follow the regional dip of the limbs of the

Courthouse syncline toward its axial trace, which is roughly coincident with Courthouse Wash. The ground water discharges along the base of the Moab Member as springs and seeps in side alcoves of Courthouse Wash and Sevenmile Canyon.

The potentiometric surface in the unconfined Moab Member aquifer fluctuates within limits. In areas where the Moab Member crops out, water infiltrates into the rocks during precipitation and snowmelt events, and the water table rises. The effect of the rise is slowly transmitted by hydraulic pressure down dip to the springs and seeps, resulting in a small fluctuation in discharge. There are no other sources of water to the springs, so increased withdrawal of ground water from the Moab Member aquifer upgradient of the springs and seeps could reduce their discharge. Water levels in the confined Moab Member aquifer area would be even more sensitive to pumping than those in the unconfined aquifer, because the storage coefficient of the confined aquifer is likely considerably less than the specific yield of the unconfined aquifer.

We believe that very little subsurface discharge from the Moab Member aquifer takes place below the springs and seeps. Accordingly, the springs and seeps are the only large natural outlets of the aquifer, and the aquifer system as a whole is in a steady-state condition; that is, the average annual recharge to the aquifer is approximately balanced by the average annual discharge of the springs and seeps. This steady-state condition has existed for quite some time as indicated by the riparian ecologic systems that have developed near the springs and seeps.

Geochemical data indicate that the residence time of ground water within the Moab Member aquifer is relatively short, consistent with the relatively short and shallow flow path suggested by the geologic setting of the system.

Courthouse Wash Boundary Spring is physically and hydrologically connected with the confined Moab Member aquifer underlying private and state-owned land west and north of the spring, including existing water wells west of the spring. The impact of the existing water wells on spring flow is not known but, based on the well sizes and estimated recharge area (figure 22), is probably small. Significant future increases in ground-water withdrawal from the confined Moab Member aquifer would, however, likely decrease the flow of Courthouse Wash Boundary Spring. Ground-water withdrawal from the Moab Member aquifer down plunge along the Courthouse syncline hinge zone (generally northwest) from Courthouse Wash Boundary Spring could impact recharge to the spring by reversing the potentiometric-surface gradient. Ground-water withdrawal up dip (generally west and east) from the spring would likely dewater the aquifer locally, capturing some of the recharge to the spring, before reversing the potentiometric-surface gradient.

The western spring group is supplied by unconfined Moab Member aquifer on public land to the southwest. The Moab Member aquifer is truncated by the Moab fault southwest of the western spring group. Withdrawal of ground water from this relatively small recharge area would strongly impact flow in the western spring group. The recharge area for the eastern spring group is on National Park Service land, so the likelihood of future withdrawal that would impact the flow of these springs is low.

## CONCLUSIONS

Springs in the study area form three geographic and hydrologic groups, separated by canyons cut into, and locally through, the Moab Member aquifer. Each spring group has a distinct and separate recharge area. The northern group, including Courthouse Wash Boundary Spring, is along the west side of Courthouse Wash north of its confluence with lower Sevenmile Canyon; the western group, including Sevenmile Canyon Boundary Spring and Poison Ivy Spring, is along the south side of lower Sevenmile Canyon and the west side of Courthouse Wash below its confluence with lower Sevenmile Canyon; and the eastern group, including Sleepy Hollow Spring, is along the east side of Courthouse Wash. These springs issue from the shallow Moab Member aquifer in the Jurassic Moab Member of the Curtis Formation. The Moab Member is a fine- to medium-grained, well-sorted, eolian sandstone composed of quartz grains cemented by calcite.

Spring-water chemistry indicates that two types of water are present in the Courthouse-Sevenmile spring system. Courthouse Wash Boundary Spring discharges sodium-calcium-bicarbonate type water, whereas Sevenmile Canyon Boundary Spring and the other sampled springs discharge calcium-bicarbonate type water. Because the springs discharge ground water after relatively short travel times in the subsurface, the water chemistry reflects only near-surface processes - infiltration of meteoric water and reaction with less resistant cements in the rocks. The temporal consistency of water chemistry and discharge from Sevenmile Canyon Boundary Spring and Poison Ivy Spring suggest that only one recharge source and aquifer contribute to the flow of these springs. The slight variability in discharge and the water chemistry of Courthouse Wash Boundary Spring suggests that some of its water comes from outside of the Moab Member aquifer.

Ground-water flow in the Moab Member aquifer is controlled by local topography, the impermeable lower contact of the formation, and regional structure. Ground water flows in the lower part of the Moab Member, above the underlying Slick Rock Member of the Entrada Sandstone. The high hydraulic conductivity of the solution-widened contact, the presence of low-permeability deposits on the top of the Slick Rock Member, and the lower hydraulic conductivity of the Slick Rock Member combine to prevent ground water from percolating below the Moab Member. The limbs of the Courthouse syncline and local topography both slope toward Courthouse Wash and direct ground-water flow to the wash.

Most springs and seeps in the study area issue from the lower contact or from cross-bed-truncation planes within the lower 25 feet (8 m) of the Moab Member aquifer. Courthouse Wash Boundary Spring and a nearby spring in the northern spring group issue from joints and cross-bed planes in the upper part of the Moab Member.

Local precipitation and snowmelt recharge the shallow, unconfined ground-water system in the parts of the Moab Member aquifer that contribute to the flow of the western and eastern spring groups. Recharge results from the downward infiltration of precipitation through fractures and directly into exposed rock of the Moab Member. We estimate that recharge to the Moab Member is about 0.5 inch per year (1 cm/yr). Courthouse Wash Boundary Spring receives re-

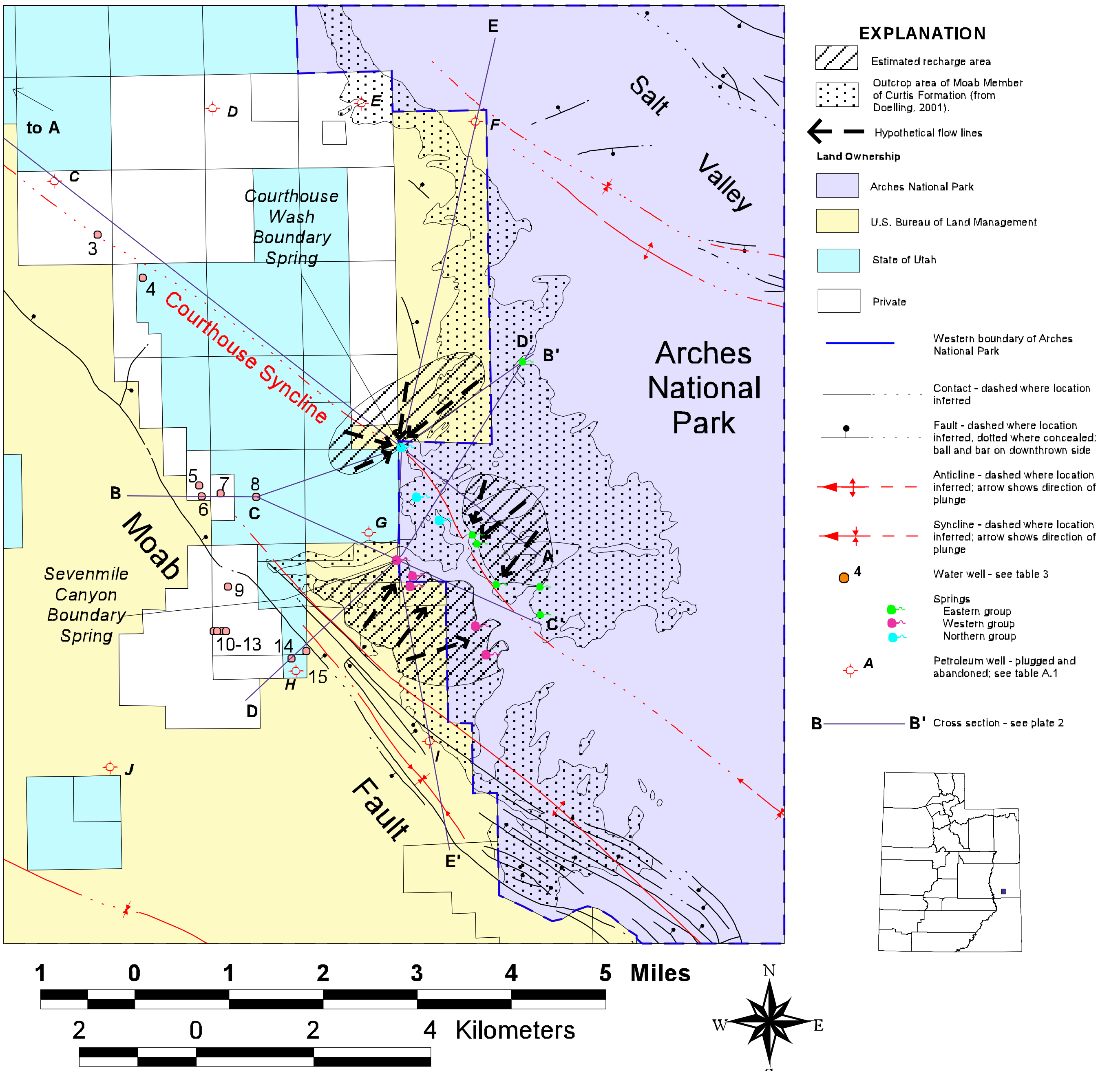



*Figure 22. Schematic representation of estimated recharge areas for Courthouse Wash Boundary Spring and the eastern and western spring groups.*

charge from both the unconfined and confined parts of the Moab Member aquifer. The confined Moab Member aquifer is in the subsurface west and north of Courthouse Wash Boundary Spring. Recharge mechanisms to the confined aquifer are uncertain but may include flow from the north in the hanging wall damage zone of the Moab fault, and infiltration of precipitation through the overlying Morrison and Summerville Formations.

We used water-budget and catchment-area methods to estimate the land-surface areas contributing to flow in the Courthouse-Sevenmile spring system, and a travel-time method to estimate aquifer areas. Of these methods, the water-budget method provides the best estimate of the size of the recharge areas for the western and eastern spring groups because it assumes that they obtain water only from infiltration of local precipitation and snowmelt, consistent with our concept of the hydrologic system for these springs. Sleepy Hollow Spring of the eastern spring group requires recharge on about 0.64 square mile (1.7 $km^2$) of Moab Member outcrop. The eastern spring group requires recharge on about 1.04 square miles (2.7 $km^2$) of Moab Member outcrop to support its observed discharge, consistent with the exposure area of about 7.5 square miles (19 $km^2$) adjacent to and upgradient of the springs. Sevenmile Canyon Boundary Spring requires recharge on about 0.67 square mile (1.7 $km^2$) of Moab Member outcrop. The western spring group requires recharge on about 1.5 square miles (3.9 $km^2$) of Moab Member outcrop to support its observed flow, consistent with the existing exposure area of about 2.0 square miles (5.2 $km^2$) adjacent to and upgradient of the western spring group.

The water-budget and catchment-area methods yield similar recharge-area estimates for Courthouse Wash Boundary Spring. Courthouse Wash Boundary Spring requires recharge from about 1.05 square miles (2.7 $km^2$) of the Moab Member aquifer to support its observed flow. This recharge comes from the unconfined and confined parts of the Moab Member aquifer in unknown proportions.

Due to their relatively low flows and limited recharge areas, all three spring groups would likely be adversely affected by increases in ground-water withdrawal from their recharge areas and adjacent parts of the Moab Member aquifer. Courthouse Wash Boundary Spring is particularly vulnerable, because (1) it marks the farthest upstream point of perennial flow in Courthouse Wash, (2) its flow is most sensitive to changes in water levels and pressure in the Moab Member aquifer, and (3) its recharge area lies below land with the greatest potential for future ground-water development.

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# GLOSSARY

Definitions are from Jackson (1997), with modification by the authors. Many of the terms appear only in the description of map units in the appendix. Italicized words are cross-referenced in the glossary. Some words in the glossary are found only in the definitions of other words, not in the text.

*Alluvial* – Pertaining to or composed of *alluvium*.

*Alluvium* – A general term for clay, silt, sand, gravel, or similar unconsolidated *detrital* material, deposited during comparatively recent geologic time by a stream or other body of running water, as a sorted or semisorted sediment in the bed of the stream or on its flood plain or delta, or as a cone or fan at the base of a mountain slope.

*Anhydrite* – A mineral consisting of anhydrous calcium sulfate: $CaSO_4$.

*Anticline* – A fold, the core of which contains stratigraphically older rocks, and is convex upward.

*Aquifer* - A body of rock or sediment that contains sufficient saturated permeable material to conduct ground water and to yield significant quantities of water to wells and springs.

*Aquitard* - An impermeable layer that creates confined ground-water conditions, in which ground water is under pressure significantly greater than that of the atmosphere.

*Arkose* - A *feldspar*-rich sandstone, commonly coarse grained and pink or reddish, that is typically composed of angular to subangular grains that may be either poorly or moderately well sorted; *quartz* is usually the dominant mineral, with *feldspars* constituting at least 25%; matrix commonly includes clay minerals, mica, iron oxide, and fine-grained rock fragments.

*Arkosic* – Said of a sedimentary rock having the composition of *arkose*.

*Base flow* - Streamflow derived from the permanent ground-water system. Typically, base flow is not subject to wide fluctuations and represents spring and seep discharge minus losses due to evapotranspiration, disregarding storm events.

*Breccia* – A coarse-grained *clastic* rock composed of angular broken rock fragments held together by mineral cement or in a fine-grained matrix.

*Calcarenite* – A limestone consisting predominantly of sand-size carbonate grains.

*Calcite* – A common rock-forming mineral – $CaCO_3$.

*Chalk* – A soft, pure, earthy, fine-textured, usually white to light gray or buff limestone of marine origin, consisting almost wholly of *calcite*, formed mainly by shallow-water accumulation of calcareous shells of floating microorganisms (chiefly foraminifers) and of comminuted remains of calcareous algae set in a structureless matrix of very finely crystalline calcite.

*Chert* – A hard, dense, dull to semivitreous, *microcrystalline* or *cryptocrystalline* sedimentary rock, consisting dominantly of interlocking crystals of quartz less than about 30 microns in diameter, that may also contain impurities such as calcite, iron oxide, and the remains of siliceous and other organisms. It has a tough, splintery to conchoidal fracture, and may be variously colored. Chert occurs as nodular or concretionary segregations (chert nodules) in limestone and dolomite, or as areally extensive layered deposits (bedded chert); it may be an original organic or inorganic precipitate, or a replacement product.

*Clastic* – Pertaining to a rock or sediment composed principally of broken fragments that are derived from preexisting rocks or minerals that have been transported some distance from their places of origin.

*Conglomerate* – A coarse-grained *clastic* sedimentary rock, composed of rounded to subangular fragments larger than 2 mm in diameter typically containing fine-grained particles in the interstices, and commonly cemented by calcium carbonate, iron oxide, silica, or hardened clay; the consolidated equivalent of gravel.

*Conjugate* – Said of two faults formed during the same deformational period and intersecting with an acute dihedral angle.

*Coquina* – A *detrital* limestone composed wholly or chiefly of mechanically sorted fossil debris that experienced abrasion and transport before reaching the depositional site.

*Cross-bed* - A single bed, inclined at an angle to the main planes of stratification.

*Cross-bedding* – Cross-stratification in which the *cross-beds* are more than 1 cm in thickness.

*Cryptocrystalline* – Said of a texture of a rock consisting of crystals that are too small to be recognized and separately distinguished even under the ordinary microscope (although crystallinity may be shown by the use of the electron microscope).

*Detrital* – Pertaining to or formed from *detritus*.

*Detritus* – A collective term for loose rock and mineral material that is worn off or removed by mechanical means, such as sand, silt, and clay, derived from older rocks and moved from its place of origin.

*Diapir* – A dome or anticline in which the overlying rocks have been ruptured by the squeezing-out of plastic core material.

*Dip* - The inclination of a planar surface (for example, bedding or a fault), as measured relative to horizontal and in a vertical plane that is perpendicular to the *strike* of the surface.

*Eolian* – Pertaining to the wind; especially said of such deposits as dune sand and loess, of sedimentary structures such as wind-formed ripple marks, or of erosion and deposition accomplished by the wind.

*Fault* - A discrete surface or zone of discrete surfaces separating two rock masses across which one rock mass has slid past the other.

*Feldspar* – A group of abundant rock-forming minerals, generally divided into two compositional groups, (1) the plagioclase feldspar series: $CaAl_2Si_2O_8$ to $NaAlSi_3O_8$, and (2) the alkali feldspar series: $(K,Na)AlSi_3O_8$.

*Fold* - A curve or bend of a planar structure such as rock strata or bedding planes.

*Foliation* – A general term for a planar arrangement of textural or structural features in any type of rock, especially the locally planar fabric in a rock defined by fissility.

*Footwall* - The lower block of a non-vertical fault.

*Fracture* - A general term for any surface within a material across which there is no cohesion; includes *joint* and *fault*.

*Gouge* - a thin layer of soft, fault-comminuted rock material in the core of a fault.

*Hanging wall* - The upper block of a non-vertical *fault*.

*Hinge line* – The line or boundary between regions of opposite dip in a *fold*.

*Hinge zone* – A broad and/or complex and/or poorly defined *hinge line*.

*Hydraulic conductivity* - A coefficient of proportionality describing the rate at which a fluid can flow through a permeable medium. Hydraulic conductivity is a function of the physical properties of the porous or fractured medium and of the density and viscosity of the fluid. Typically reported in units of feet or meters per day.

*Joint* - A planar or nearly planar fracture in rock, along which negligible relative movement has occurred.

*Limestone* – A sedimentary rock consisting chiefly of calcium carbonate, principally in the form of the mineral *calcite*; formed by either organic or inorganic processes, and may be detrital, chemical, *oolitic*, crystalline, or recrystallized; many are highly fossiliferous and represent ancient shell banks or coral reefs; rock types include *micrite*, *calcarenite*, *coquina*, *chalk*, and *travertine*.

*Micrite* - A rock or rock matrix composed of carbonate mud with crystals less than 4 micrometers in diameter.

*Microcrystalline* – Said of a texture of a rock, consisting of crystals that are small enough to be visible only under the microscope.

*Mudstone* - A fine-grained sedimentary rock in which the proportions of clay and silt are approximately equal.

*Normal drag* – A fold that appears to have formed in response to fault motion.

*Normal fault* - A fault along which the *hanging wall* has moved downward relative to the *footwall*.

*Oolite* – A sedimentary rock, usually a *limestone*, made up chiefly of *ooliths* cemented together.

*Oolith* – One of the small round or ovate accretionary bodies in a sedimentary rock. It is usually formed of calcium carbonate, in successive concentric layers, commonly around a nucleus such as a shell fragment, an algal pellet, or a quartz sand grain, in shallow, wave-agitated water.

*Oolitic* – Pertaining to an *oolite*, or to a rock or mineral made up of ooliths.

*Permeability* - A coefficient describing the rate at which fluid can flow through a porous or fractured medium.

*Quartz* – Crystalline silica, an important rock-forming mineral: $SiO_2$.

*Reverse fault* - A fault that dips greater than 30 degrees, along which the hanging wall has moved upward relative to the footwall.

*Sandstone* - A medium-grained *clastic* sedimentary rock composed of abundant rounded or angular fragments of sand size and more or less firmly united by a cementing material.

*Shale* - A laminated, indurated rock with >67% clay-sized minerals.

*Siltstone* - An indurated silt having the texture and composition of shale but lacking its fine lamination or fissility.

*Slickenside* - a highly polished surface that is the result of frictional sliding.

*Striae* - plural of striation, defined as one of a series of linear grooves or scratches, generally parallel, inscribed on a rock surface, by faulting as used in the context of this report.

*Strike* - The angle a planar feature makes relative to north, as measured in a horizontal plane.

*Syncline* - A *fold*, the core of which contains stratigraphically younger rocks, and is convex downward.

*Thrust fault* - A *fault* that dips 30 degrees or less, along which the hanging wall has moved upward relative to the footwall.

*Transmissivity* – The rate at which a fluid is transmitted through a unit width of an aquifer under a hydraulic gradient. Typically reported in units of square feet or square meters per day.

*Travertine* – A dense, finely crystalline massive or concretionary *limestone*, of white, tan, or cream color, commonly having a fibrous or concentric structure and splintery fracture, formed by rapid chemical precipitation of calcium carbonate from solution in surface and ground waters as by agitation of stream water or by evaporation around the mouth or in the conduit of a spring, especially a hot spring.

*Unconformity* - A substantial break or gap in the geologic record where a rock unit is overlain by another that is not next in stratigraphic succession.

# APPENDIX

| Era | Period | | Epoch | Age | Age estimates in Ma[1] |
|---|---|---|---|---|---|
| Cenozoic | Quaternary | | Holocene | | 0.01 |
| | | | Pleistocene | | 1.6 |
| | Tertiary | Neogene | Pliocene | | 5 |
| | | | Miocene | | 24 |
| | | Paleogene | Oligocene | | 38 |
| | | | Eocene | | 55 |
| | | | Paleocene | | 66 |
| Mesozoic | Cretaceous | | Late | Maastrichtian | 74.5 (4) |
| | | | | Campanian | 84.0 (4.5) |
| | | | | Santonian | 87.5 (4.5) |
| | | | | Coniacian | 88.5 (2.5) |
| | | | | Turonian | 91.0 (2.5) |
| | | | | Cenomanian | 97.5 (2.5) |
| | | | Early | Aptian | 113 (4) |
| | | | | Albian | 119 (9) |
| | | | | Neocomian | 144 (5) |
| | Jurassic | | Late | | 163 (15) |
| | | | Middle | | 187 (34) |
| | | | Early | | 208 (18) |
| | Triassic | | Late | | 230 (22) |
| | | | Middle | | 240 (22) |
| | | | Early | | 245 (20) |

1. *Age estimates are from Hansen (1991), with uncertainties in parentheses, except where none are reported.*

| Era | Period | Epoch | Age | Age estimates in Ma[1] |
|---|---|---|---|---|
| | | | | 245 (20) |
| Paleozoic | Permian | Late | | 258 |
| | | Early | | 286 (12) |
| | Pennsylvanian | Late | | 290 |
| | | Middle | | 310 |
| | | Early | | ~330 |
| | Mississippian | Late | | 340 |
| | | Early | | 360 (10) |
| | Devonian | Late | | 374 (18) |
| | | Middle | | 387 (28) |
| | | Early | | 408 (12) |
| | Silurian | Late | | 421 (12) |
| | | Early | | 438 (12) |
| | Ordovician | Late | | 458 (16) |
| | | Middle | | 478 (16) |
| | | Early | | 505 (32) |
| | Cambrian | Late | | 523 (36) |
| | | Middle | | 540 (28) |
| | | Early | | 570 |
| Proterozoic | Late Proterozoic | | | 900 |
| | Middle Proterozoic | | | 1600 |
| | Early Proterozoic | | | 2500 |
| Archean | Late Archean | | | 3000 |
| | Middle Archean | | | 3400 |
| | Early Archean | | | 3800? |

***Figure A.1.*** *Geologic time scale, after Palmer (1983) and Hansen (1991).*

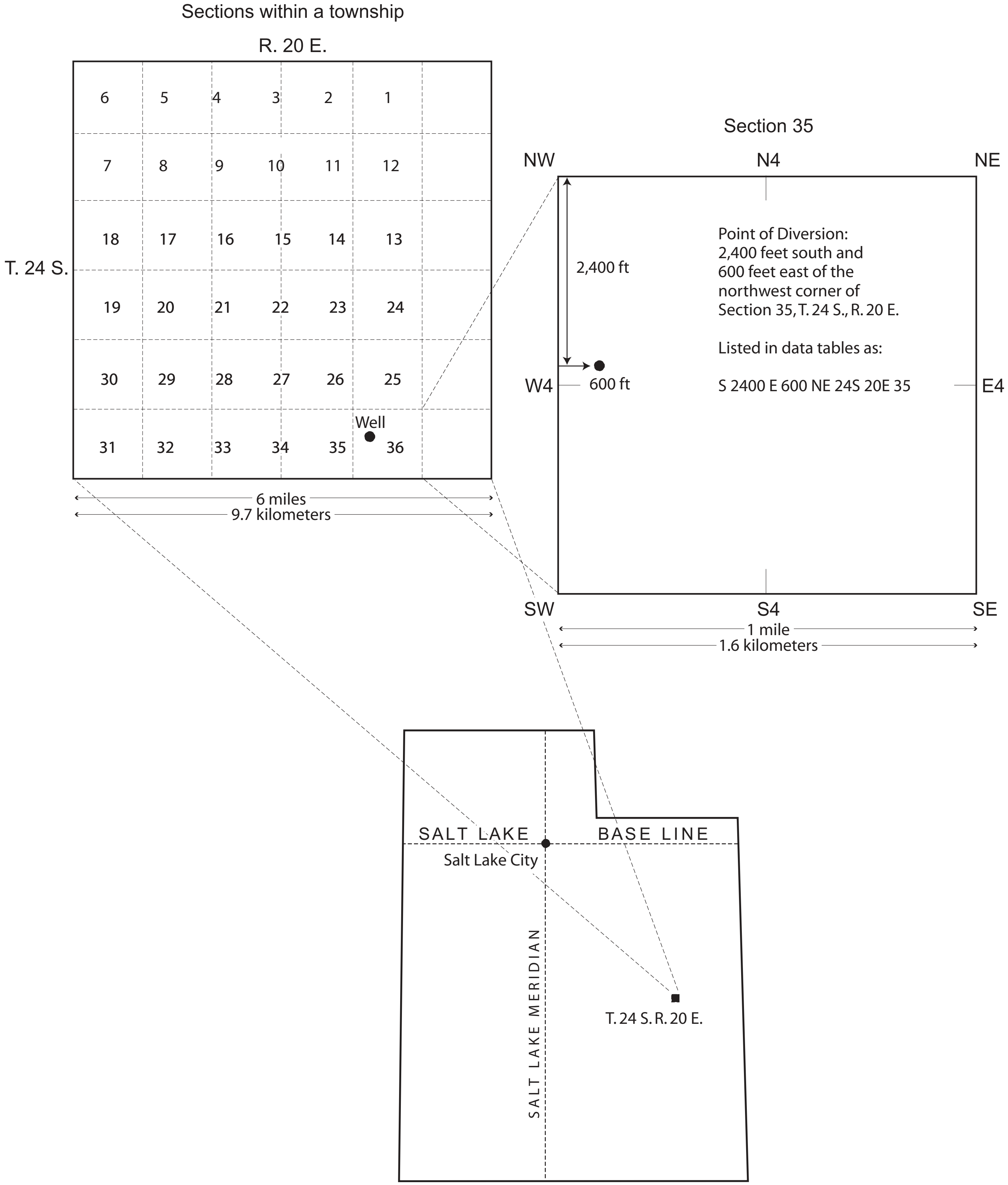



***Figure A.2.*** *Numbering system for wells in Utah - Point of diversion convention.*

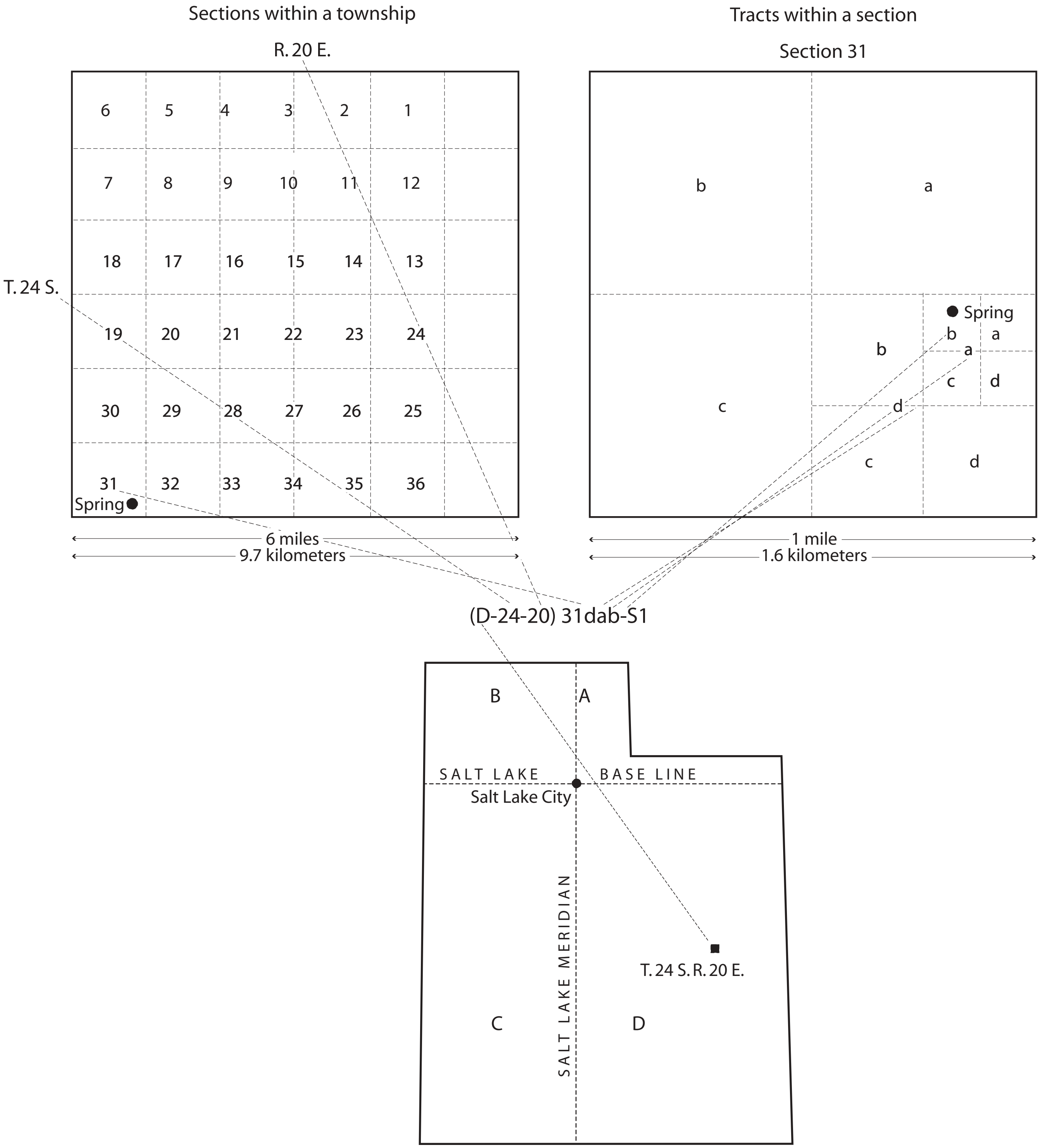



***Figure A.3.*** *Numbering system for springs in Utah - U.S. Geological Survey convention.*

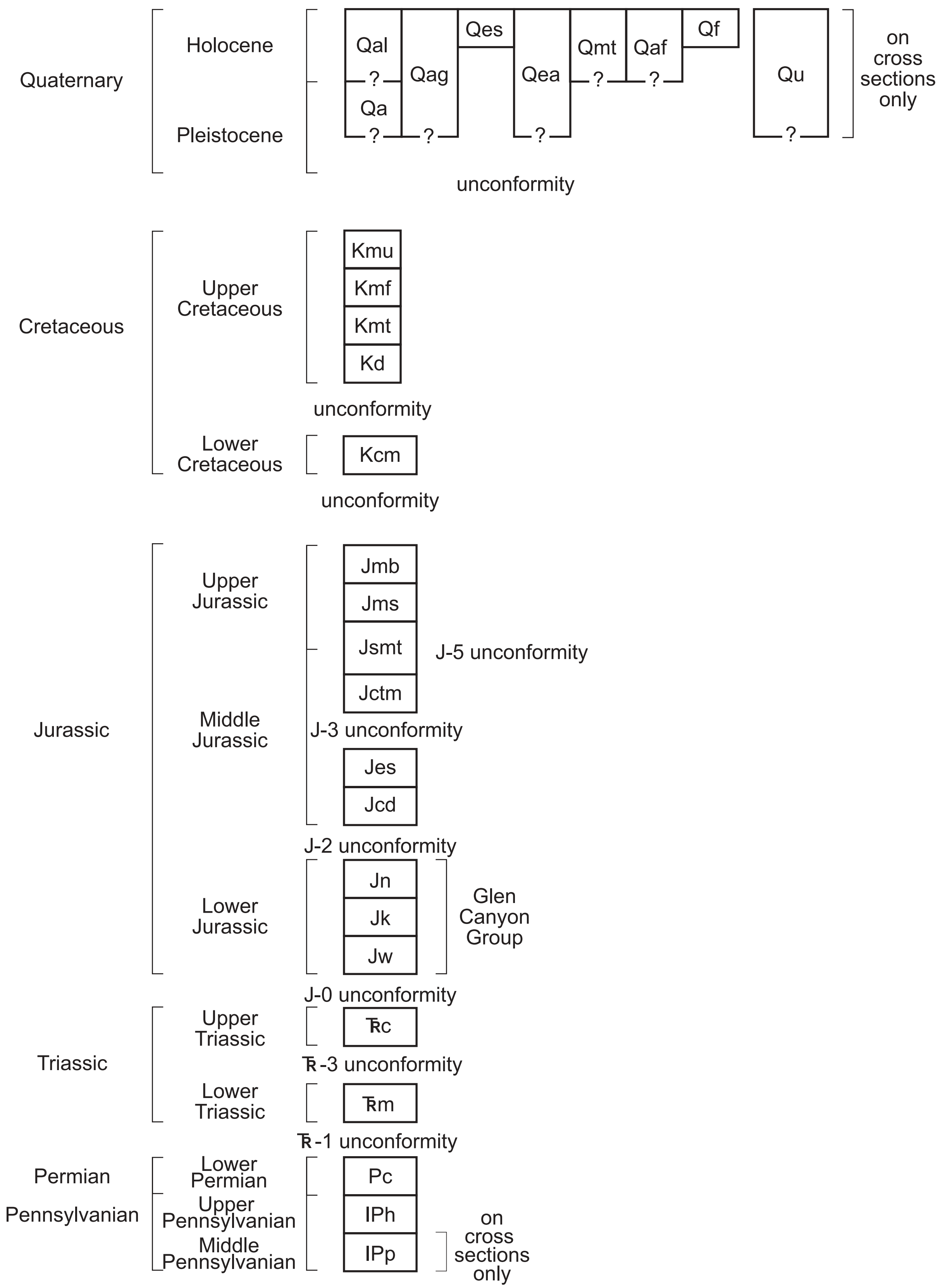



***Figure A.4.*** *Correlation of geologic units shown on figures 6 and 7, and plate 1.*

***Figure A.4.*** *(continued)* ***Description of Geologic Units from Doelling (2001).***

## Quaternary Deposits

**Qal** Stream alluvium -- Sand, silt, clay, granules, pebbles, and sparse cobbles adjacent to more active stream courses; unconsolidated, poorly to well-sorted channel-fill and low terrace depostis; thickness varies widely, but commonly less than 10 meters (3.3 ft) thick; Holocene to late Pleistocene.

**Qag** Alluvial gravel, undifferentiated -- Clast sizes vary from deposit to deposit; no particular geomorphic form or location; thickness commonly 5 meters (16 ft) or less.

**Qea** Mixed eolian and alluvial deposits -- Sand and silt of eolian origin interspersed with silt, sand, and gravel of fluvial origin; generally dominated by eolian deposits; commonly displays a well-developed caliche soil horizon at the top; thickness 10 meters (33 ft) or less; Holocene to middle Pleistocene.

**Qes, Qed** Eolian deposits -- Well-sorted sand and silt; deposited in sheets (Qes) and dunes (Qed); commonly fills hollows in sandstone outdrops or collects on the lee sides of cliffs and slopes; thickness 15 meters (50 ft) or less; mostly Holocene.

## Cretaceous Rocks

**Kmu** Upper Shale (Blue Gate) member of Mancos Shale -- Mostly light- to dark-gray, marine, thinly laminated to thin-bedded, slope-forming shale, mudstone, and siltstone interbedded with subordinate yellow-brown to yellow-gray, mostly very fine- to fine-grained calcareous sandstone that crops out in several thin mappable (Kms) zones of subtle ledges and cliffs; the middle, more sandy part of the upper shale member that contains most of the ledges is the Prairie Canyon Member of Cole and others (1997); zone of thin-bedded, fine-grained sandstone at top; lower contact with Ferron Sandstone Member is gradational; about 1,020 meter (3,350 ft) thick; Campanian to Toronian.

**Kmf** Ferron Sandstone Member of Mancos Shale -- Brown-gray to yellow-gray, marine, fine-grained sandstone, sandy mudstone, and carbonaceous shale; fissile to thin bedded; generally forms two sandsstone cuestas with a slope of dark-gray to black carbonaceous shale between them; locally fossiliferous; lower contact is a subtle scour surfacelocally overlain by lenticular lag deposits of pebbly, medium- to coarse-grained sandstone; 15-40 meters (50-130 ft) thick; Toronian.

**Kmt** Tununk Shale Member of mancos Shale -- Light- to dark-gray, marine shale or mudstone; contains fine-grained sandy zones, especially near the top; slope forming; locally contains concretionary Coon Springs Bed in the upper third of the unit; lower contact with Dakota is abrupt but conformable. The lower contact is an unconformity where the Dakota is missing (Western exposures) and marked by change from green (Cedar City Fm.) to gray shale; 45 to 120 meters (145-390 ft) thick, generally thicker to west; Toronian to Cenomanian.

**Kd** Dakota Sandstone -- Yellow-gray to brown sandstone, conglomerate sandstone, and conglomerate interbedded with gray mudstone, carbonaceous shale, coal, and claystone; commonly forms cliffs and ledges; commonly divisible in the east part of the quadrangle into upper and lower cliff-forming sandstone and conglomerate and a middle, slope-forming mudstone unit; scoured into the Cedar Mountain or Burro Canyon Formations; 0 to 37 meters (0-120 ft) thick, discontinuous in west part of quadrangle, thickens eastward; Cenomanian.

**Kcm** Cedar Mountain Formation -- Drab olive-green to variegated mudstone and brown to gray sandstone, gritstone, conglomerate, and limestone; mudstone is slope forming, other rock types form ledges; locally contains petrified wood; lower contact (unconformity) is placed at base of a prominent sandstone or conglomerate ledge or cliff above the brighter variegated mudstone of the Brushy Basin Member of the Morrison Formation; correlative with the Burro Canyon Formation; 12 to 76 meters (40-250 ft) thick, thins irregularly eastward; Albian.

## Jurassic Rocks

**Jmb** Brushy Basin Member of Morrison Formation -- Variegated (purple, green, white, orange) mudstone interbedded with gray, white, or brown conglomeratic sandstone, conglomerate, nodular limestone, and gritstone; slope forming with subtle ledges; purple and lavender hues dominate in most areas, but bright green dominates in Cache Valley and in the southern part of the Salt Vally anticline; layers of bentonitic claystone are common, outcrops are generally prone to slumping; lower contact placed at the base of the mudstone sequence or at the base of the lowest conglomerate ledge; 90 to 135 meters (295-450 ft) thick; Upper Jurassic.

**Jms** Salt Wash Member of Morrison Formation -- Light-yellow-gray sandstone interbedded with red and gray mudstone and siltstone; sandstone is fine to coarse grained, cross-bedded, and forms medium to thick lenses; mudstone and siltstone form slopes or recesses between sandstone ledges; lower contact at base of first thick sandstone bed above the red or lavender siltstone of the Tidwell Member of the Morrison Formation; locally intertongues with Tidwell siltstones; 40 to 90 meters (130-300 ft) thick; Upper Jurassic.

**Jsmt** Tidwell Member of Morrison Formation and Summerville Formation, undivided -- Divisible in field, but too thin to map separately at the 1:100,000 scale. Tidwell Member (Jmt) consists of calcareous, thin-bedded lavender, maroon, and light-gray siltstone, light-gray, thin- to thick bedded, very fine-grained sandstone, and gray thin-bedded or nodular limestone; all slope forming; limestone locally contains large white chert concretions; west of 110° W., locally intertongues with thick white gypsum bodies; 6

***Figure A.4.*** *(continued)*

## Jurassic Rocks *(continued)*

to 20 meters (20-65 ft) thick. Summerville unconformably (J-5 unconformity) overlain by Tidwell Member. In areas where combined with the Tidwell, the Summerville is gray, tan, brown, and red, mostly fine-grained, thin-bedded sandstone and siltstone that forms a steep slope and becomes ledgy near the top; 2-21 meters (6-69 ft) thick. Upper and Middle Jurassic.

Jctm

Moab Member of Curtis Formation (member of Entrada Sandstone on previous maps) -- Ligh-yellow-gray, fine- to medium-grained, cross-bedded, massive, and cliff-forming sandstone; forms a tongue between the summerville and Entrada Formations and pinches out in the western part of the quadrangle; rests directly on the Slick Rock member in the east; the lower contact with the Slick Rock Member of the Entrada Sandstone is placed at the base of a prominent parting or subtle line, probably the J-3 unconformity of Pipiringos and O'Sullivan (1978), which has considerable relief in the Dewey area; 0 to 42 meters (0-138 ft) thick (including the main Curtis where both are present); Middle Jurassic.

Jes

Slick Rock Member of Entrada Sandstone -- Mostly orange-red or banded orange-red and white sandstone; generally fine-grained, eolian cross-bedded; massive with local discontinuous partings; resistant and smooth weathering, but not as resistant as the Moab Member of the Entrada Sandstone: locally pocked with abundant small spherical holes (with diameters up to 10 centimeters) in outcrop; the lower contact is commonly crenulated or contorted above the darker red-brown sandstone of the Dewey Bridge Member of the Carmel Formation; 43 to 152 meters (140-500 ft) thick, thinning eastward; Middle Jurassic.

Jcd

Dewey Bridge member of Carmel Formation (member of Entrada Sandstone on previous maps) -- Upper half is dark-red, muddy, earthy, fine-grained sandstone; lower half is interbedded dark-red, red-brown, light-brown, and yellow-gray, fine- to medium-grained sandstone; upper half commonly has contorted, nodular, or indistinct bedding and locally contains white beds; upper half forms slopes or recesses between the overlying Slick Rock Member of the Entrada Sandstone and the lower half; lower half is more resistant, is commonly calcareous and cherty, and forms scabs on the underlying Navajo Sandstone; yellow-gray beds in the lower half resemble the underlying Navajo Sandstone, but are flat bedded; lower half is locally missing, expecially in the east; lower contact is the J-2 unconformity of Pipiringos and O'Sullivan (1978); 8 to 72 meters (25-235 ft) thick, generlaly thinning eastward; Middle Jurassic.

Jn Jnl

Navajo Sandstone -- Mostly light-hued, fine- to medium-grained, eolian cross-bedded, massive sandstone; lower third commonly weathers to a cliff, the remainder into domes and rounded knolls; locally contains thin, hard, gray limestone beds (Jnl); lower contact placed at the top of a thick, white to pink sandstone in the Kayenta Formation; 0 to 225 meters (0-740 ft) thick, pinches out to the northeast over the Uncompahgre uplift; Lower Jurassic.

Jk

Kayenta Formation -- Red-brown, lavender-gray, fine- to coarse-grained, medium- to thick-bedded sandstone; contains local white and dark-brown beds, intraformational conglomerate, and limestone; forms thick ledges; generally contains abundant red slope-forming siltstone in upper third; lower contact is a scoured surface in the massive orange-brown Wingate Sandstone; 30 to 90 meters (100-300 ft) thick; Lower Jurassic.

Jw

Wingate Sandstone -- Orange-brown, dark-brown-weathering, fine-grained, massive sandstone; forms vertical cliff along canyon walls, commonly stained with desert varnish; abrupt contact with underlying Chinle Fomration placed at base of massive, cliff-forming sandstone or on top of thick, orange-brown, flat-bedded sandstone (J-O) unconformity) below which typical Chinle slope-forming siltstones and sandstones are found; 75-137 meters (250-450 ft) thick; Lower Jurassic.

## Triassic Rocks

TRc

Chinle Formation -- Red-brown sandstone, siltstone, conglomeratic sandstone, and mudstone; forms steep slope with Moenkopi Formation below; has basal member of quartzose gritstone or sandstone and mottled siltstone and sandstone beneath an unconformity; contins multiple intraformational unconformities adjacent to salt diapirs; lower contact is the TR-3 unconformity of Pipiringos and O'Sullivan (1978), which is slightly angular; 0 to 275 meters (0-900 ft) or more thick, greatest thickness in rim synclines adjacent to salt-cored anticlines and locally missing on anticlines; only 12 to 30 meters (40-100 ft) cover Percambrian rocks on the Uncompahgre uplift to the northeast; Upper Triassic.

TRm

Moenkopi Formation -- Red-orange, chocolate-brown, and medium-brown sandstone, silty sandstone, and minor siltstone and conglomerate; generally divisible into two to four members, but are undivided on the map; lower contact is the TR-1 unconformity of Pipiringos and O'Sullivan (1978), which is slightly angular and is found at the top of the more red-brown sandstone of the underlying Cutler Formation; total thickness is 0 to 400 meters (0-1,300 ft) or more, thinning regionally eastward and may be missing on the Uncompahgre uplift

***Figure A.4.*** *(continued)*

## Triassic Rocks *(continued)*

in the northeast and very thick in rim synclines adjacent to salt-cored anticlines; Middle (?) to Lower Triassic.

## Permian Rocks

Pc

Cutler Formation -- Interbedded red-brown subarkosic, arkosic, and micaceous sandstone and lavender-brown conglomerate; sandstone is fine to coarse grained and gritty in eastern exposures; low- to high-angle crossbeds, thin bedded to massive, and forms smooth and rounded ledges; conglomerate is mostly pebbles to 13-centimeter (5-inch) cobbles, but cobbles exceeding 30 centimeters (1 ft) or more in diameter are common in the eastern part of the quadrangle; mostly quartzite, granite, felsite, gneiss, and schist clasts; matrix is poorly sorted, fine- to coarse-grained sandstone, with grains of quartz, lithic fragments, mica, feldspar, and unidentified black minerals; laminated to indistinct bedding; weathers to smooth irregular slopes or gentle ledges; lower contact is placed above a gray limestone ledge that contains Late Pennsylvanian (Virgilian) fusulinids; 0 to 2,450 meters (0-8,000 ft) thick; missing over some salt-cored anticlines, thickest at the west edge of the Uncompahgre uplift; as much as 1,000 meters (3,300 ft) exposed; 75 meters (245 ft) of gray-white, cross-bedded quartzose sandstone at the top of the Cutler Formation in the north part of the southwest flank of Castle Valley may be an outcrop of White Rim Sandstone; Lower Permain.

## Pennsylvanian Rocks

Ph

Honaker Trail Formation -- Interbedded sandstone, siltstone, limestone, and subarkosic sandstone; limestone is commonly fossiliferous; the lower contact is not exposed, but the unit is juxtaposed against Paradox Formation caprock on the southwest flank of the Onion Creek salt-cored anticline; 0 to 1,525 meters (0-5,000 ft) or more thick, thickening eastward to the west edge of the Uncompahgre uplift, missing on the Uncompahgre uplift and over some salt-cored anticlines; maximum surface thickness is less than 300 meters (985 ft); Upper Pennsylvanian (Virgilian-Missourian).

***Table A.1**. Records of oil-test wells in study area[1].*

| ID[2] | Operator | Well Name | API Number | Township | Range | Section | Spot[3] | Elevation | Total Depth | Log[4] |
|---|---|---|---|---|---|---|---|---|---|---|
| A | EQUITY OIL COMPANY | 1 STATE | 4301910361 | 23 S | 19 E | 36 | 1650 FSL 330 FEL | 4585 | 6769 | Kd 320; Jms 862; Js 959; Jctm 1605; Jcd 1726; Jn 2172; Jk 2544; Jw 2708; TRc 3070; TRm 3780 |
| B | MOUNTAIN FUEL SUPPLY CO | 2 KLONDIKE UNIT | 4301930272 | 24 S | 19 E | 22 | 1860 FSL 793 FEL | 4765 | 7830 | Jctm 46; Jcd 520; Jn 680; Jk 1570; Jw 2004; TRc 2254; TRm 2929; Pc 3228; IPh 5444 |
| C | LADD PETROLEUM CO. | 1 SALT VALLEY | 4301931112 | 24 S | 20 E | 16 | 500 FNL 2130 FWL | 4456 | 11330 | TRc 468; TRm 837; Pc 1375; IPh 2861; IPp 4406 |
| D | TIGER OIL CO | 12-11 STATE | 4301930455 | 24 S | 20 E | 11 | 1980 FNL 660 FWL | 4927 | 12357 | Jctm 300; Jcd 400; Jn 560; Jk 1580; Jw 1680; TRc 2010; TRm 2170 |
| E | SHELL OIL COMPANY | 1 LEGGETT | 4301911035 | 24 S | 20 E | 12 | 1715 FNL 1673 FEL | 4636 | 5600 | Jn 90; Jk 536; Jw 593; TRc 940; TRm 1398; Pc 1575; IPh 3097; IPp 4426 |
| F | FERGUSON & BOSWORTH | 1 CULLEN-HS PET-GOVT | 4301930122 | 24 S | 21 E | 7 | 660 FNL 660 FEL | 4845 | 4964 | Jk 885; Jw 1173; TRc 1570; TRm 2380; Pc 4809 |
| G | UNION OIL CO OF CALIFORNIA | 1 STATE | 4301930032 | 24 S | 20 E | 36 | 575 FSL 1836 FEL | 4434 | 7534 | Jn 1720; TRc 2545; TRm 3395; Pc 5478; IPh 9170 |
| H | GREAT LAKES CARBON CORP | 1 STATE | 4301911472 | 25 S | 20 E | 2 | 300 FSL 660 FEL | 4598 | 3665 | Jctm 754; Jn 1307; Jk 2237; Jw 2335; TRc 2618; TRm 3544; Pc 4465; IPh 6708; IPp 8678 |
| I | ARI-MEX OIL & EXPLOR INC | 1-7 SKIP-FEDERAL | 4301930418 | 25 S | 21 E | 7 | 1742 FSL 1557 FWL | 4738 | 2300 | IPp 2900 |
| J | CHANDLER & ASSOC. INC. | 16-9 MOAB-FEDERAL | 4301930910 | 25 S | 20 E | 9 | 388 FSL 547 FEL | 4996 | 9968 | IPp 4496 |
| K | GENERAL CRUDE OIL CO | 1 BIG ROCK-BARTLETT | 4301930050 | 25 S | 19 E | 26 | 820 FNL 615 FEL | 5436 | 8875 | Jctm 150; Jn 680; Jk 1180; Jw 1410; TRc 1810; TRm 2535; Pc 5115 |

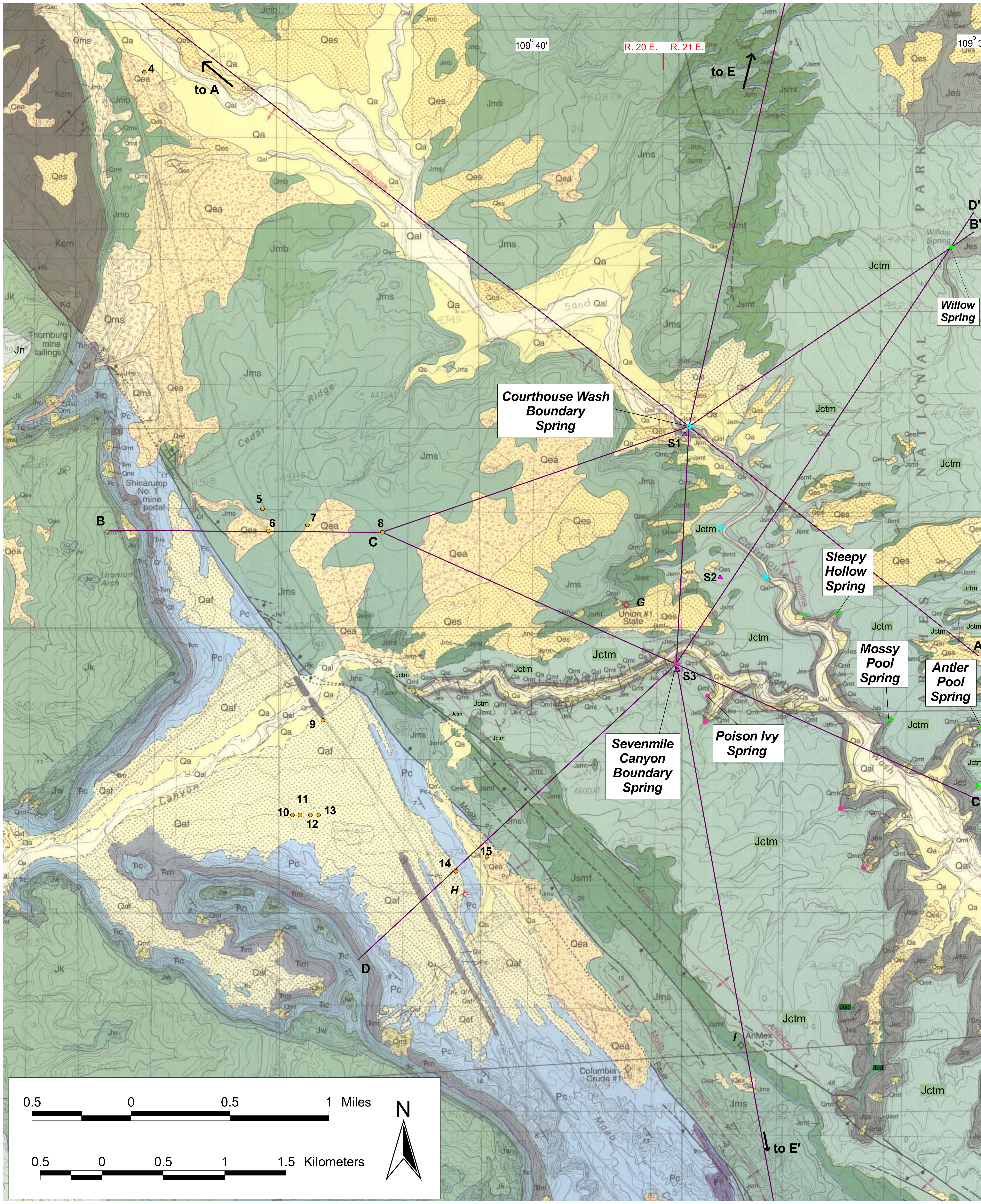
**Notes**

1. Data from Utah Division of Oil, Gas and Mining records.
2. Corresponds to letters on figures 3 and 7 and plate 1.
3. Distances in feet from north (FNL), south (FSL), east (FEL), and west (FWL) section boundaries.
4. Values are depth to top of formation in feet below reference elevation. Unit abbreviations and map symbols shown on figure 7 and plate 1.

Plate 1
Special Study 108
Utah Geological Survey

# Geologic Map of the Courthouse Wash - Sevenmile Canyon Area, Grand County, Utah

Base from U.S. Geological Survey Merrimac Butte 7.5 minute quadrangle.
Geology from Doelling and Morgan (2000). See Doelling and Morgan (2000) and Doelling (2001) for detailed lithologic descriptions.




## EXPLANATION

Contact - dashed where location inferred

Normal Fault - dashed where location inferred, dotted where concealed; ball and bar on downthrown side

Anticline - dashed where location inferred; arrow shows direction of plunge

Syncline - dashed where location inferred; arrow shows direction of plunge

5 Strike and dip of bedding

1 Water well - see table 3

Springs
- Eastern group
- Western group
- Northern group

A Petroleum exploration well - plugged and abandoned; see table A.1

B——B' Cross section - see plate 2; some sections are truncated by map boundary

S1 Scanline sample site - see table 9 and text

### Map Units

**Quaternary**

- **Qf** Fill and disturbed material (not shown on figure 7)
- **Qal** Modern alluvium
- **Qa** Older alluvium (included in units Qal and Qea on figure 7)
- **Qaf** Alluvial-fan deposits (included in units Qea and Qes on figure 7)
- **Qes** Eolian sand deposits
- **Qea** Mixed eolian and alluvial deposits
- **Qmt** Talus and colluvium (not shown on figure 7)
- **Qer** Mixed eolian and residual deposits

**Cretaceous**

- **Kd** Dakota Sandstone - Sandstone, conglomeratic sandstone, mudstone, and shale
- **Kcm** Cedar Mountain Formation - Mudstone, sandstone, conglomerate, and limestone

**Jurassic**

Morrison Formation
- **Jmb** Brushy Basin Member - Mudstone, conglomeratic sandstone, conglomerate, and limestone
- **Jms** Salt Wash Member - Sandstone, mudstone, and siltstone
- **Jsmt** Tidwell Member of Morrison Formation and Summerville Formation, undivided - Siltstone, sandstone, and limestone
- **Jctm** Moab Member of Curtis Formation[1] - Cross-bedded sandstone
- **Jes** Slick Rock Member of Entrada Sandstone - Cross-bedded sandstone
- **Jcd** Dewey Bridge Member of Carmel Formation[1] - Sandstone
- **Jn** Navajo Sandstone - Cross-bedded sandstone
- **Jk** Kayenta Formation - Sandstone
- **Jw** Wingate Sandstone - Sandstone

**Triassic**

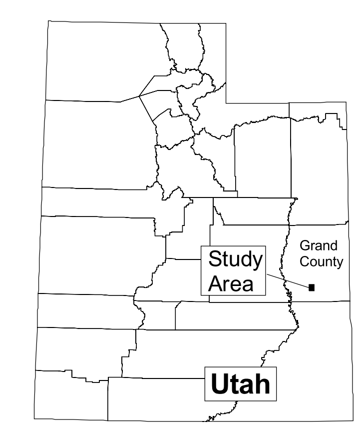
- **Ћc** Chinle Formation - Sandstone, siltstone, conglomeratic sandstone, and mudstone
- **Ћm** Moenkopi Formation - Sandstone, silty sandstone, and siltstone

**Permian**

- **Pc** Cutler Formation - Arkosic, micaceous sandstone and conglomerate

**Pennsylvanian**

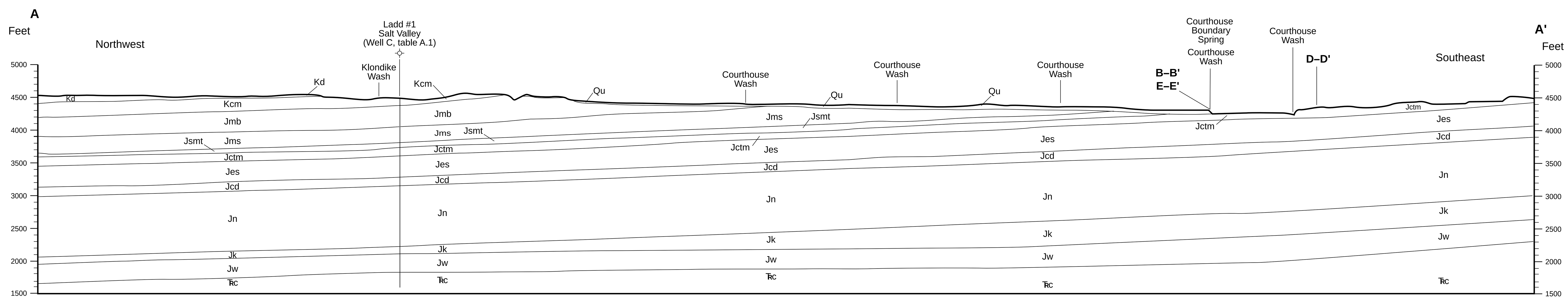
- **IPh** Honaker Trail Formation - Sandstone, siltstone, limestone, and subarkosic sandstone

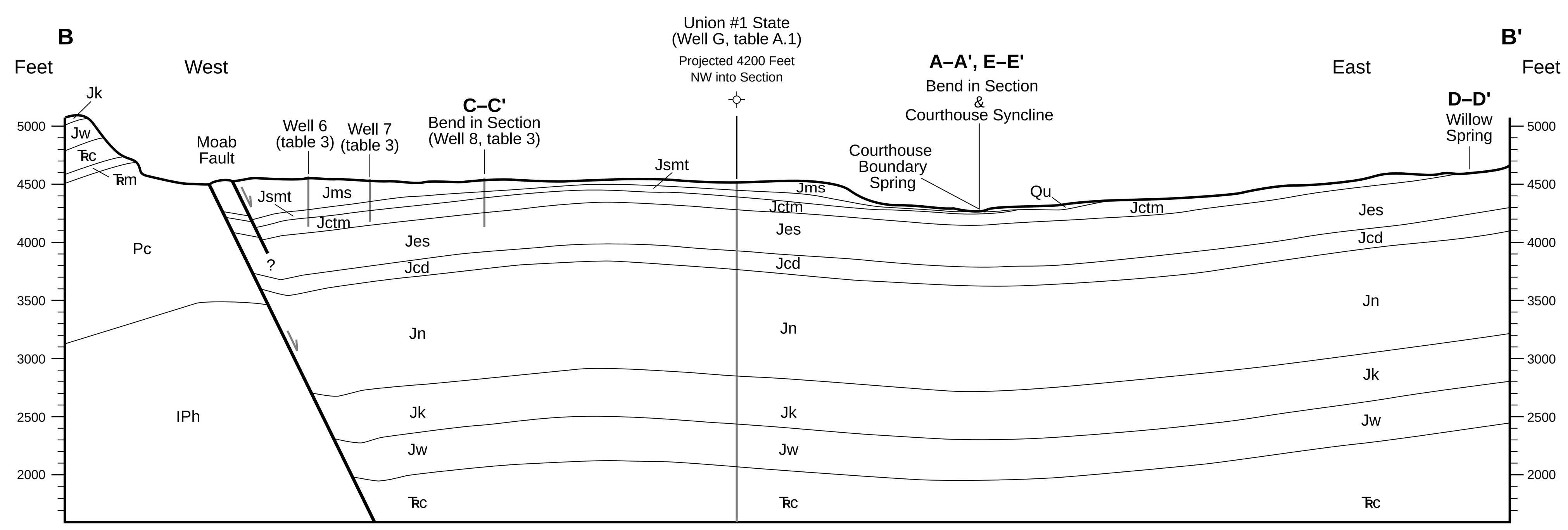


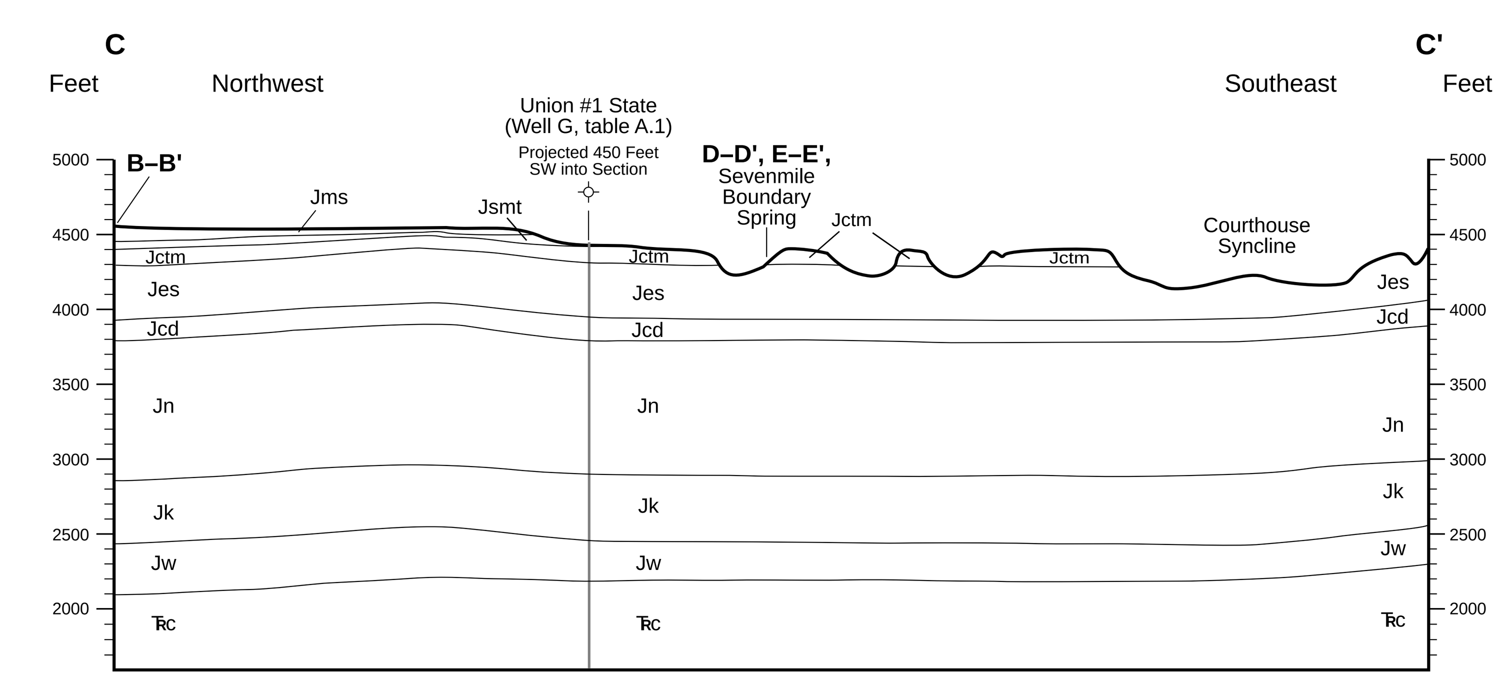

1 - Formerly mapped as a member of the Entrada Sandstone; see Doelling (2001) for explanation of nomenclature revision.

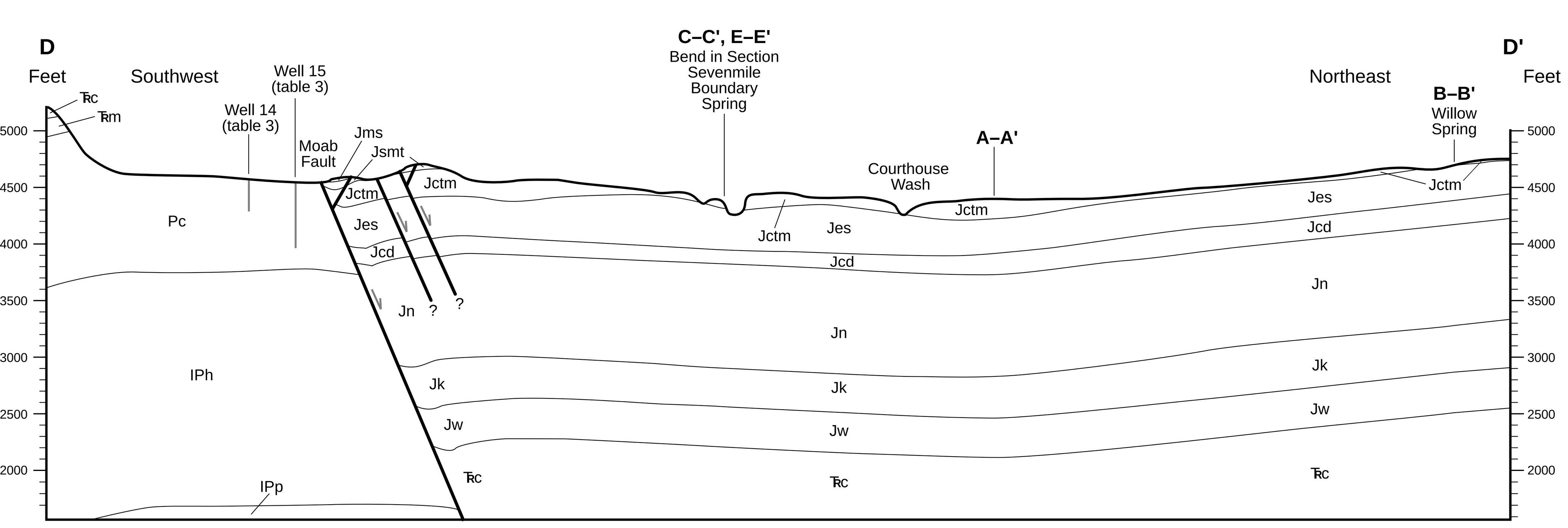
# Cross Sections of the Courthouse Wash – Sevenmile Canyon Area, Grand County, Utah

Locations on Figure 7 and Plate 1



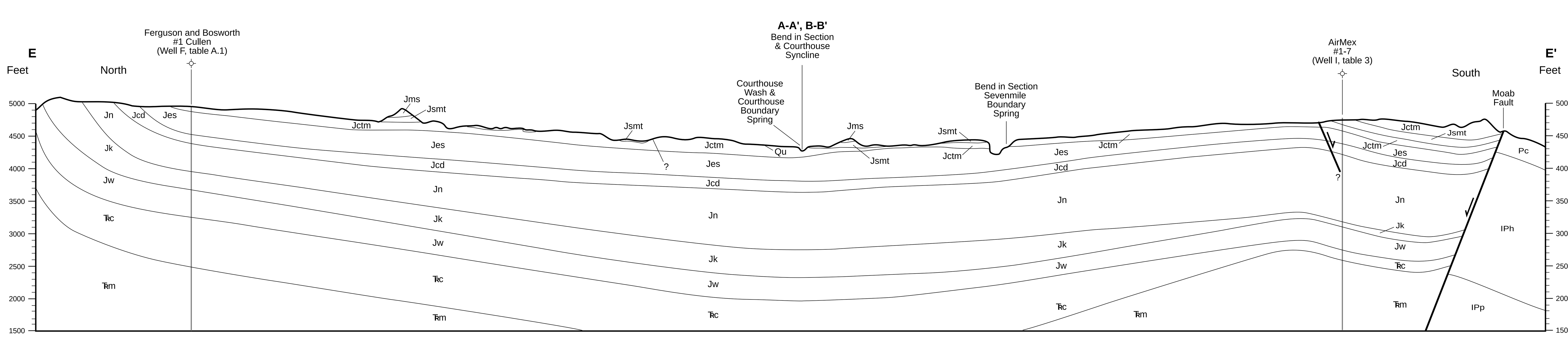



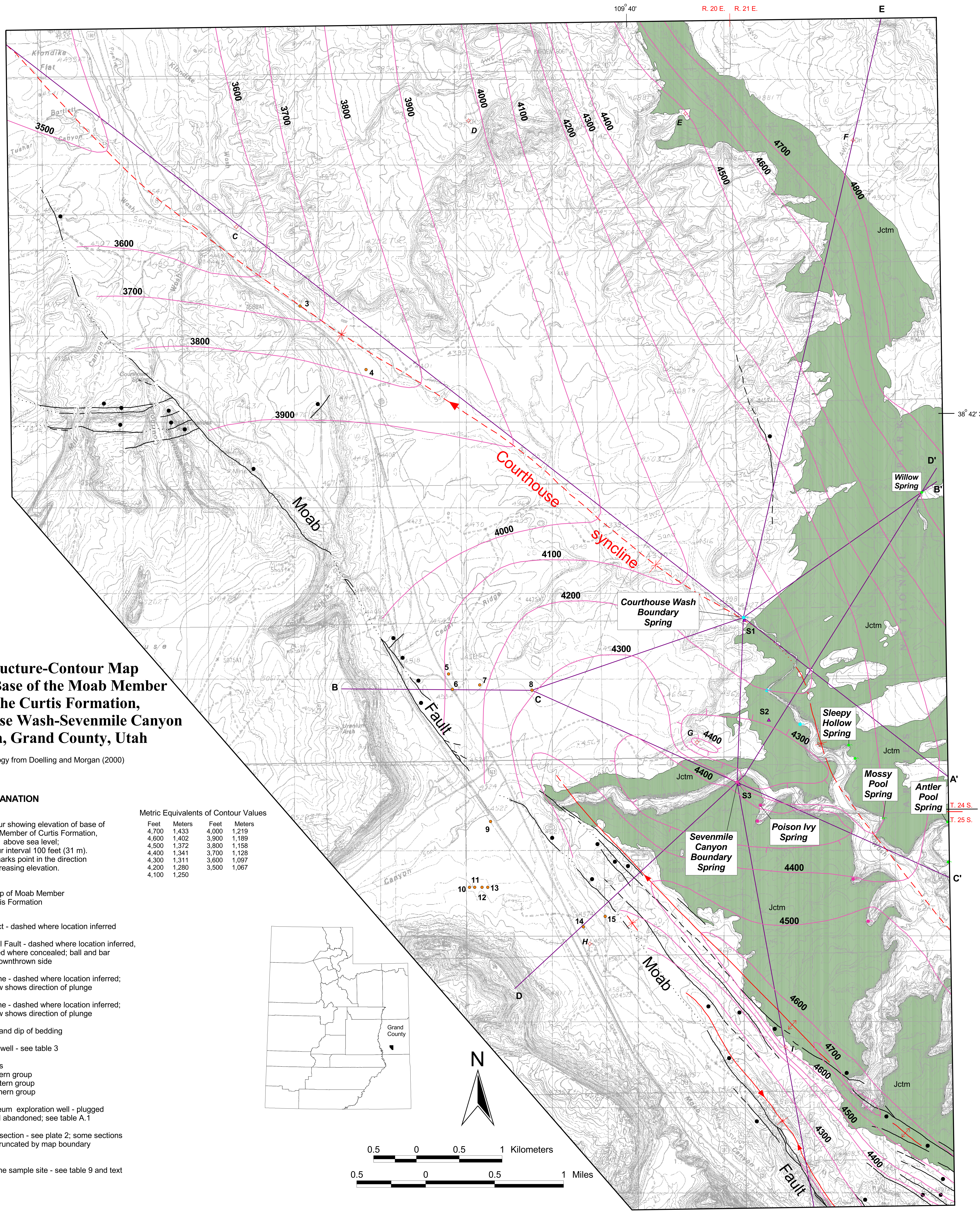




VERTICAL EXAGGERATION ON ALL SECTIONS 2X.

See figure 5 and appendix for unit descriptions






# Structure-Contour Map of the Base of the Moab Member of the Curtis Formation, Courthouse Wash-Sevenmile Canyon Area, Grand County, Utah

Geology from Doelling and Morgan (2000)

## EXPLANATION

4300 — Contour showing elevation of base of Moab Member of Curtis Formation, in feet above sea level; contour interval 100 feet (31 m). Tick marks point in the direction of decreasing elevation.

Metric Equivalents of Contour Values

| Feet | Meters | Feet | Meters |
|---|---|---|---|
| 4,700 | 1,433 | 4,000 | 1,219 |
| 4,600 | 1,402 | 3,900 | 1,189 |
| 4,500 | 1,372 | 3,800 | 1,158 |
| 4,400 | 1,341 | 3,700 | 1,128 |
| 4,300 | 1,311 | 3,600 | 1,097 |
| 4,200 | 1,280 | 3,500 | 1,067 |
| 4,100 | 1,250 | | |

Outcrop of Moab Member of Curtis Formation

Contact - dashed where location inferred

Normal Fault - dashed where location inferred, dotted where concealed; ball and bar on downthrown side

Anticline - dashed where location inferred; arrow shows direction of plunge

Syncline - dashed where location inferred; arrow shows direction of plunge

5 — Strike and dip of bedding

4 — Water well - see table 3

Springs
- Eastern group
- Western group
- Northern group

A — Petroleum exploration well - plugged and abandoned; see table A.1

B—B' — Cross section - see plate 2; some sections are truncated by map boundary

S1 — Scanline sample site - see table 9 and text