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# Geology of Paleozoic Rocks in the Upper Colorado River Basin in Arizona, Colorado, New Mexico, Utah, and Wyoming, Excluding the San Juan Basin

Regional Aquifer-System Analysis

Professional Paper 1411–A


USGS
science for a changing world

# Geology of Paleozoic Rocks in the Upper Colorado River Basin in Arizona, Colorado, New Mexico, Utah, and Wyoming, Excluding the San Juan Basin

*By* ARTHUR L. GELDON

REGIONAL AQUIFER-SYSTEM ANALYSIS—
UPPER COLORADO RIVER BASIN, EXCLUDING SAN JUAN BASIN

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1411-A

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## FOREWORD

### THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

The Regional Aquifer-System Analysis (RASA) program represents a systematic effort to study a number of the Nation's most important aquifer systems which, in aggregate, underlie much of the country and which represent important components of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system, and accordingly transcend the political subdivisions to which investigations have often arbitrarily been limited in the past. The broad objective for each study is to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies to develop an understanding of the natural, undisturbed hydrologic system and the changes brought about by human activities, and to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA program is assigned a single Professional Paper number beginning with Professional Paper 1400.

Charles G. Groat
Director

# CONTENTS

## PLATES

[Plates are in pocket]

# ILLUSTRATIONS

# TABLES

## METRIC CONVERSION FACTORS

| *Multiply* | *By* | *To obtain* |
|---|---|---|
| acre | 0.4047 | hectare (h) |
| acre-foot (acre-ft) | 0.001233 | cubic hectometer ($hm^3$) |
| | 1,233.0 | cubic meter ($m^3$) |
| acre-foot per year (acre-ft/yr) | 0.001233 | cubic hectometer per year ($hm^3/yr$) |
| cubic foot per second per mile (($ft^3s$)/mi) | 0.04557 | cubic meter per second per kilometer (($m^3/s$)/km) |
| foot (ft) | 0.3048 | meter (m) |
| | 30.48 | centimeter (cm) |
| foot per day (ft/d) | 0.3048 | meter per day |
| foot per year (ft/yr) | 0.3048 | meter per year (m/yr) |
| foot squared per day ($ft^2/d$) | 0.09290 | meter squared per day ($m^2/d$) |
| gallon per minute (gal/min) | 0.06309 | liter per second (L/s) |
| inch (in.) | 2.540 | centimeter (cm) |
| | 25.40 | millimeter (mm) |
| inch squared ($in.^2$) | 6.452 | centimeter squared ($cm^2$) |
| mile (mi) | 1.609 | kilometer (km) |
| square foot ($ft^2$) | 0.0929 | square meter ($m^2$) |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |

A millidarcy is $0.987 \times 10^{-11}$ centimeter squared. Temperature in degrees Fahrenheit (°F) can be converted to temperature in degrees Celsius (°C) by using the following equation:

$$°C = 5/9\ (°F-32)$$

## ALTITUDE DATUM

Altitudes in this report are referenced to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929, or mean sea level.

# GEOLOGY OF PALEOZOIC ROCKS IN THE UPPER COLORADO RIVER BASIN IN ARIZONA, COLORADO, NEW MEXICO, UTAH, AND WYOMING, EXCLUDING THE SAN JUAN BASIN

*By* Arthur L. Geldon

ABSTRACT

The geology of the Paleozoic rocks in the Upper Colorado River Basin in Arizona, Colorado, New Mexico, Utah, and Wyoming, was studied as part of the U.S. Geological Survey's Regional Aquifer-System Analysis Program to provide support for hydrogeological interpretations. The study area is segmented by numerous uplifts and basins caused by folding and faulting that have recurred repeatedly from Precambrian to Cenozoic time.

Paleozoic rocks in the study area are 0–18,000 feet thick. They are underlain by Precambrian igneous, metamorphic, and sedimentary rocks and are overlain in most of the area by Triassic formations composed mostly of shale. The overlying Mesozoic and Tertiary rocks are 0–27,000 feet thick.

All Paleozoic systems except the Silurian are represented in the region. The Paleozoic rocks are divisible into 11 hydrogeologic units.

The basal hydrogeologic unit consisting of Paleozoic rocks, the Flathead aquifer, predominantly is composed of Lower to Upper Cambrian sandstone and quartzite. The aquifer is 0–800 feet thick and is overlain gradationally to unconformably by formations of Cambrian to Mississippian age.

The Gros Ventre confining unit consists of Middle to Upper Cambrian shale with subordinate carbonate rocks and sandstone. The confining unit is 0–1,100 feet thick and is overlain gradationally to unconformably by formations of Cambrian to Mississippian age.

The Bighorn aquifer consists of Middle Cambrian to Upper Ordovician limestone and dolomite with subordinate shale and sandstone. The aquifer is 0–3,000 feet thick and is overlain unconformably by Devonian and Mississippian rocks.

The Elbert-Parting confining unit consists of Lower Devonian to Lower Mississippian limestone, dolomite, sandstone, quartzite, shale, and anhydrite. It is 0–700 feet thick and is overlain conformably to unconformably by Upper Devonian and Mississippian rocks.

The Madison aquifer consists of two zones of distinctly different lithology. The lower (Redwall-Leadville) zone is 0–2,500 feet thick and is composed almost entirely of Upper Devonian to Upper Mississippian limestone, dolomite, and chert. The overlying (Darwin-Humbug) zone is 0–800 feet thick and consists of Upper Mississippian limestone, dolomite, sandstone, shale, gypsum, and solution breccia. The Madison aquifer is overlain conformably by Upper Mississippian and Pennsylvanian rocks.

The Madison aquifer in most areas is overlain by Upper Mississippian to Middle Pennsylvanian rocks of the Four Corners confining unit. The lower part of this confining unit, the Belden-Molas subunit, consists of as much as 4,300 feet of shale with subordinate carbonate rocks, sandstone, and minor gypsum. The upper part of the confining unit, the Paradox–Eagle Valley subunit, in most places consists of as much as 9,700 feet of interbedded limestone, dolomite, shale, sandstone, gypsum, anhydrite, and halite. Locally, the evaporitic rocks are deformed into diapirs as much as 15,000 feet thick. The Four Corners confining unit is overlain gradationally to disconformably by Pennsylvanian rocks.

The uppermost Paleozoic rocks comprise the Canyonlands aquifer, which is composed of three zones with distinctly different lithologies. The basal (Cutler-Maroon) zone consists of as much as 16,500 feet of Lower Pennsylvanian to Lower Permian sandstone, conglomerate, shale, limestone, dolomite, and gypsum. The middle (Weber–De Chelly) zone consists of as much as 4,000 feet of Middle Pennsylvanian to Lower Permian quartz sandstone with minor carbonate rocks and shale. The upper (Park City–State Bridge) zone consists of as much as 800 feet of Lower to Upper Permian limestone, dolomite, shale, sandstone, phosphorite, chert, and gypsum. The Canyonlands aquifer is overlain disconformably to unconformably by formations of Triassic and Jurassic age.

## INTRODUCTION

In anticipation of increased water use for the development of local coal and oil resources and to meet the water needs of an expanding population, the U.S. Geological Survey from 1981 to 1990 systematically appraised the ground-water resources of the Upper Colorado River Basin (UCRB). According to Taylor and others (1983, 1986), specific objectives of this study (henceforth referred to as the UCRB-RASA) included:

1. Identification of aquifers and confining units among consolidated sedimentary rocks of Cambrian to Tertiary age;
2. Determination of the extent, thickness, and hydrologic characteristics of aquifers and confining units;
3. Determination of the availability of water from the aquifers;

4. Determination of the geochemical characteristics of the ground water;
5. Analysis of the regional flow system under steady-state conditions; and
6. Analysis of the flow-system responses to hypothetical ground-water withdrawal or injection.

The regional analysis of the Upper Colorado River Basin is described in the several chapters of USGS Professional Paper 1411. The UCRB-RASA is one of several U.S. Geological Survey RASA studies nationwide, as discussed in the foreword to this report.

Because the occurrence, movement, and chemical quality of water in the region are in large part controlled by the structure and stratigraphy of the host rocks, a lengthy analysis was made of the stratigraphy of the Paleozoic rocks in the UCRB. This analysis attempted to (1) correlate stratigraphic units from area to area; (2) clarify problems of ill-defined geologic unit boundaries in areas where differing schemes of stratigraphic nomenclature come together; and (3) provide a lithological basis for grouping a large number of geologic units into a relatively small number of hydrogeologic units (aquifers and confining units). This report describes the extent, thickness, lithology, and contact relations of the Paleozoic rocks in the UCRB, as related to their occurrence in hydrogeologic units listed in plate 1. This report also describes the Precambrian and Triassic rocks in contact with the Paleozoic rocks. Sources for the stratigraphic material used for interpretation include unpublished logs of petroleum industry boreholes prepared by the American Stratigraphic Company, lithologic logs of damsite exploration holes provided by the U.S. Bureau of Reclamation (written commun., 1983–85), and measured sections and other information from numerous geologic reports cited in the text and listed in the "Selected References" section.

## LOCATION OF STUDY

The UCRB, as defined by the Colorado River Compact of 1922, encompasses the drainages of the Green and Colorado Rivers above the mouth of the Paria River at Lees Ferry, Ariz., and the internally drained Great Divide Basin of Wyoming. The UCRB includes about 113,500 mi$^2$ of land in western Colorado, eastern Utah, southwestern Wyoming, northeastern Arizona, and northwestern New Mexico. Because most of the San Juan Basin, an area of about 14,600 mi$^2$, was excluded for separate investigation, this report does not cover most of the land in New Mexico and some of the land in southwestern Colorado and northeastern Arizona that are in the San Juan Basin region of the UCRB. However, the RASA study area includes some land peripheral to the UCRB from which geologic and hydrologic information was obtained to support interpretations. The area of the UCRB-RASA is about 100,000 mi$^2$.

The UCRB, including the San Juan Basin, extends from latitude 35°46′ N. to latitude 43°27′ N. and from longitude 105°38′ W. to longitude 112°19′ W. Maximum dimensions of this area are about 560 mi from north to south and about 320 mi from east to west. Principal towns in the UCRB include Grand Junction, Montrose, Delta, Paonia, Glenwood Springs, Aspen, Craig, Steamboat Springs, Meeker, Gunnison, Cortez, and Durango, Colo.; Price, Vernal, Manila, Moab, Monticello, and Blanding, Utah; Rock Springs, Green River, Pinedale, and Kemmerer, Wyo.; Page and Kayenta, Ariz.; and Shiprock and Farmington, N. Mex.

## PREVIOUS INVESTIGATIONS

Since the pioneering geologic work of the Powell, Hayden, Wheeler, and King surveys of the 1860's and 1870's, numerous geologic studies have been made in parts of the UCRB, particularly in the Colorado Plateaus province and in the Uinta Mountains. Areas described in some of the more important literature are shown in figure 1.

Particularly useful in this investigation were reports that contained regional, subregional, or statewide syntheses of geologic information. Notable among these efforts is the Geologic Atlas of the Rocky Mountain Region, published in 1972 by the Rocky Mountain Association of Geologists. Organized by stratigraphic system, papers in this atlas by Lochman-Balk (Cambrian), Foster (Ordovician), Baars (Devonian), Craig (Mississippian), Mallory (Pennsylvanian), and Rascoe and Baars (Permian) contain extensive discussions of stratigraphic relations between, and the depositional history of, Paleozoic stratigraphic units. Updates of this information for the State of Colorado were provided in papers by Ross and Tweto, De Voto, and Maughan compiled in the book "Colorado Geology," published in 1980 by the Rocky Mountain Association of Geologists. The stratigraphy of Utah is discussed in some detail by Hintze (1973); the stratigraphy of Arizona is discussed cursorily by Wilson (1962). A book entitled "Rocky Mountain Sedimentary Basins," published in 1965 by the American Association of Petroleum Geologists, is a compilation of papers on the depositional and tectonic history of areas within and peripheral to the UCRB, including the Overthrust Belt (Armstrong and Oriel, 1965), Kaiparowits and Black Mesa Basins (Lessintine, 1965), Paradox Basin (Ohlen and McIntyre, 1965), Uinta Basin (Osmond, 1965), San Juan Basin (Peterson and others, 1965), Piceance and Eagle Basins (Quigley, 1965), and Oquirrh Basin (Roberts and others, 1965). For the Colorado Plateaus province alone, a 1983 book by Baars entitled, "The Colorado Plateau—a geologic history," contains the most comprehensive regional synthesis of previously published discussions of Paleozoic stratigraphy and geologic history.

Many subregional syntheses of information on the Paleozoic rocks were reviewed during the UCRB-RASA. Representative of these reports are studies by Baars (1958), Cooper (1960), Parker and Roberts (1963), Benson (1966), Campbell (1972), Gerhard (1972), Middleton and others (1980), and Ross (1986)

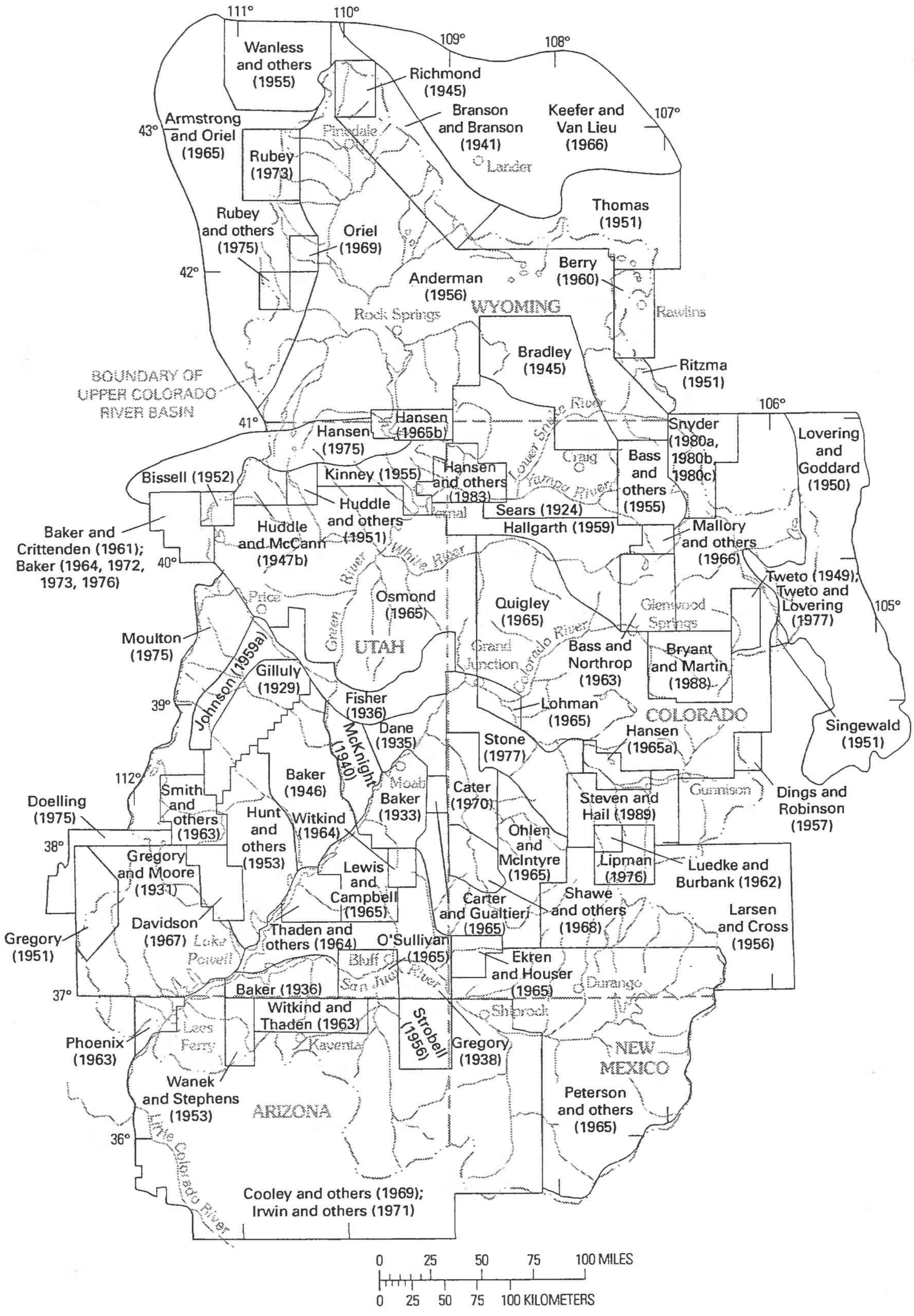



FIGURE 1.—Areas covered by representative geologic reports in the Upper Colorado River Basin and vicinity (areas of overlap not shown).

on the Cambrian to Mississippian rocks; reports by Conley (1972), Nadeau (1972), Rose (1977), Mallory (1979), McKee (1979), Roberts (1979), and Sando (1979) on the Mississippian rocks; and reports by Langenheim (1952, 1954), Wengerd and Strickland (1954), Wengerd (1957, 1958), Kunkel (1958, 1960), McKelvey and others (1959), Merrill and Winar (1961), Read and Wanek (1961), Baars (1962, 1979), Kirkland (1963), Boggs (1966), Hallgarth (1967), Mallory (1967, 1971, 1975), Maughan (1967, 1979), McKee (1967, 1975, 1982), Sheldon and others (1967), Freeman (1971), Bartleson (1972), De Voto (1972), Hite and Cater (1972), Sando and others (1975), Freeman and Bryant (1977), Irtem (1977), Welsh and others, (1979), Steele-Mallory (1982), De Voto and others (1986), Dodge and Bartleson (1986), Johnson (1987, 1989), and Johnson and others (1990) on the Pennsylvanian and Permian rocks.

### SYSTEM OF NUMBERING WELLS AND SPRINGS

Wells and springs are numbered in this report according to the U.S. Bureau of Land Management system. The first one or two letters in the site-identification number represent the principal survey meridian. The UCRB is referenced to seven principal survey meridians; symbols adopted for these meridians in this report are

G - Gila and Salt River
N - Navajo
NM - New Mexico
S - Sixth
SL - Salt Lake
U - Uintah
UT - Ute

Letters and numbers following the symbol for the principal survey meridian in the site identification number refer, in order, to quadrant, township, range, section, quarter section, quarter-quarter section, quarter-quarter-quarter section, and number of well or spring within the smallest physical boundary (multiple ground-water sites within the smallest physical boundary are numbered consecutively). Quadrants and divisions of sections are labeled from A to D in a counter-clockwise direction starting with the northeast quadrant or section division. Quadrant designations usually are upper case; section division designations usually are lower case. Zeros or dashes are used to separate quadrant, township, range, and section designations. As an example, a well numbered SC06-89-09bda$_1$ is the first well in the northeast quarter of the southeast quarter of the northwest quarter of Section 9, Township 6 South, Range 89 West, in the southwest quadrant of the Sixth principal survey meridian.

### ACKNOWLEDGMENTS

The author is indebted to Charles (Chuck) Spencer, U.S. Geological Survey, who helped gain access to the unpublished petroleum-industry logs used in this report, and to the U.S. Bureau of Reclamation (Denver, Grand Junction, and Salt Lake City offices) for providing unpublished exploration-hole logs.

## GEOLOGIC SETTING

Exposed rocks in the Upper Colorado River Basin range in age from Precambrian to Tertiary (pl. 2). Precambrian sedimentary, metamorphic, and igneous rocks crop out in the center of uplifted areas. Paleozoic rocks also crop out in uplifted areas. Mesozoic rocks have widespread surface exposure, particularly in the southern part of the area. Tertiary sedimentary rocks crop out extensively in structural basins north of the Uncompahgre Plateau. Tertiary intrusive and extrusive rocks are widespread in the Colorado Plateaus and Southern Rocky Mountains.

### STRATIGRAPHIC AND HYDROGEOLOGIC NOMENCLATURE

The extent, thickness, and lithology of Paleozoic rocks described in this report (table 1, oversize) were determined from examination of more than 700 lithologic logs of oil and gas wells and exploratory boreholes (American Stratigraphic Co., unpublished), lithologic logs of damsite boreholes (U.S. Bureau of Reclamation, unpublished), and more than 200 published surface stratigraphic sections. Data sites generally were selected at intervals of 10 to 20 mi for compiling stratigraphic information on maps and correlation diagrams. More widely spaced intervals were used in areas of sparse data, particularly in the deep structural basins of Wyoming and Utah. In thrust-faulted areas, such as the Overthrust Belt (pl. 1), part or all of a geologic formation can be repeated two or more times vertically. In these areas, fault-repeated beds were not included in calculating thicknesses of Paleozoic strata and depths to the top of the Paleozoic rocks.

Formation tops and bottoms were picked by tracing lithologic intervals between boreholes and measured sections plotted at vertical scales ranging from 1:1,200 to 1:4,800 (depending on total plotted thickness). The Paleozoic column was divided into three vertical intervals for correlation. These intervals (see table 1) were (1) the top of the Weber–De Chelly zone of the Canyonlands aquifer to the top of the Paleozoic rocks; (2) the top of the Redwall-Leadville zone of the Madison aquifer to the bottom of the Weber–DeChelly zone; and (3) the top of the Precambrian rocks to the bottom of the Redwall-Leadville zone. In many instances, formation tops and bottoms identified on geologic logs were reinterpreted.

The areal extent of individual formations, as mapped in this study, may differ from interpretations shown in other reports for some areas. Existing stratigraphic nomenclature in the UCRB is the result of over 100 years of geological investigation. One unfortunate result of numerous individual geologic efforts in isolated parts of the UCRB over this long period of time has been a system of nomenclature that varies from geographic area to geographic area without any consistent basis for recognized name changes within correlative stratigraphic sequences. Many name changes are based on facies changes of local extent; some merely reflect the limits of geographically preferred terms within a homogeneous stratigraphic sequence. Some name changes are based on inferred depositional history; others are based on relatively small variations in the age of a homogeneous stratigraphic sequence.

Formations cited in this report are lithostratigraphic units, as defined by the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983, p. 855–856). According to this code, lithostratigraphic units are recognizable only on the basis of observable rock characteristics; they cannot be based on inferred geologic history, depositional environment, or biological sequence. Nor do " * * * inferred time-spans, however measured, play [any] part in differentiating or determining the boundaries of any lithostratigraphic unit * * *. The body [of the unit] in some places may be entirely younger than in other places," provided it does not contain identifiable regional unconformities. Many of the previously established criteria for delimiting Paleozoic formations in the study area do not conform to this code.

An attempt was made in compiling stratigraphic information during this study to preserve as many of the long-established geologic names as possible but in such a manner that name changes within correlative stratigraphic sequences had a consistent basis. Accordingly, formation boundaries within correlative sequences were demarcated in this report on the basis of (1) an identifiable lithologic variation, or (2) an identifiable boundary between depositional centers. The term "equivalent" was used where geologic formations were correlated on the bases of borehole lithologic logs, but where paleontological and other information necessary for unequivocal stratigraphic designation was lacking. For example, in southwestern Colorado, rocks similar to the Bright Angel Shale and Muav Limestone, respectively, are designated "Bright Angel equivalent" and "Muav equivalent." Some of the geologic names used in this report are not used by the U.S. Geological Survey (USGS) but are used widely by academic and industry geologists in parts of the UCRB. These names were felt to be more useful for regional correlation and discussion than names accepted by the USGS. Sources for names not accepted by the USGS are cited where these names appear throughout the report.

Two types of correlative sequences were recognized: (1) Sequences of essentially homogeneous lithology that are slightly time-transgressive; and (2) sequences of diverse lithology that represent a depositional trend within an essentially integral time horizon. Examples of the first type of lithologic sequence include the basal Cambrian Ignacio-Tapeats-Tintic-Lodore-Sawatch-Flathead sandstone and quartzite sequence; the Mississippian Leadville-Redwall-Madison-Lodgepole-Mission Canyon limestone and dolomite sequence; and the Pennsylvanian and Permian De Chelly-Coconino-White Rim-Weber-Wells-Tensleep sandstone sequence (table 1). Examples of the second type of sequence include the mostly Devonian Elbert-Parting-Darby carbonate-clastic sequence; the Mississippian and Pennsylvanian Paradox-Manakacha-Round Valley-Eagle Valley-Moffat Trail carbonate-evaporite-clastic sequence; and the Permian Kaibab-Toroweap-Park City-Phosphoria-lower State Bridge-lower Goose Egg carbonate-clastic sequence (table 1).

Because the information in this report was compiled for an analysis of ground-water flow systems, stratigraphic sequences are grouped into hydrogeologic units for mapping and discussion. A hydrogeologic unit in this report is defined as a group of geologic formations or members of formations that are related stratigraphically and share hydrologic properties that are similar or vary systematically as a result of changing depositional environments. Hydrogeologic units listed in table 1 include aquifers, confining units, and their subdivisions (zones and subunits). They consist of either a single correlative sequence, such as those described in the previous paragraph, or several correlative sequences. The second type of hydrogeologic unit is represented by the Cutler-Maroon zone of the Canyonlands aquifer, which consists of a sequence of interbedded carbonate and clastic rocks (the upper member of the Hermosa Formation and equivalents) overlain by a sequence of red beds (the Cutler Group, Maroon Formation, and equivalents).

Hydrogeologic unit information was compiled initially on 1:1,000,000- and 1:2,000,000-scale maps. A 10 mi × 10 mi grid was placed over each 1:2,000,000-scale map of the individual hydrogeologic units, and the grid-center thicknesses were added to determine the total thickness of Paleozoic rocks at each grid center. Grid-center total thicknesses were contoured to determine the regional distribution of the Paleozoic rocks. A similar method combining data for Mesozoic and Tertiary rocks was used to determine depths to the top of the Paleozoic rocks, the top of the Madison aquifer, and the top of the Flathead aquifer throughout the region. Variations in the thickness of the Paleozoic rocks and depths to the top of these rocks in the UCRB and vicinity are shown on plate 3.

## PRECAMBRIAN ROCKS

The Precambrian rocks in the UCRB consist mostly of unnamed metamorphic and plutonic rocks of Archean and Proterozoic age (pl. 4). Proterozoic sedimentary rocks are preserved in a few areas (table 1).

The Archean rocks are part of the Wyoming cratonic province (Karlstrom and others, 1987, fig. 1), that extends from the Yellowstone region and Beartooth Mountains on the Montana-Wyoming border south to the northern Sierra Madre and the north flank of the Uinta Mountains (Hedge and others, 1986, fig. 1). The southern boundary of this province, the Cheyenne Belt (pl. 1), is an arcuate band of thrust faulting, recumbent folding, and mylonitization, which Duebendorfer and Houston (1987, p. 566) interpreted as a zone of crustal accretion along a passive continental margin. North of the Cheyenne Belt in Wyoming, the Archean rocks consist of a granite-gneiss complex overlain by a supracrustal sequence of quartzite, metagraywacke, metaconglomerate, slate, phyllite, schist, iron-formation, serpentinite, greenstone, and amphibolite. These metamorphic rocks are intruded by granite, granodiorite, quartz diorite, diorite, and gabbro plutons (Love and Christiansen, 1985; Hedge and others, 1986, Duebendorfer and Houston, 1987). On the north flank of the Uinta Mountains, the Red Creek Quartzite consists of intensely fractured quartzite, subordinate quartz-mica schist and amphibolite, and minor calc-silicate rock, marble, metagraywacke, and pegmatite (Hansen, 1965b, p. 22–32). The Red Creek Quartzite is approximately 2.5 billion years old and more than 20,000 ft thick (Hedge and others, 1986; Tweto, 1987). In Wyoming, Archean metamorphic rocks are 2.6 to 3.0 billion years old, whereas the plutonic rocks are 2.6 to 2.7 billion years old (Love and Christiansen, 1985; Hedge and others, 1986, pl. 1).

A second period of Proterozoic tectonic activity accompanied by igneous intrusion is indicated by 1.6- to 1.8-billion-year-old metamorphic and plutonic rocks that extend from the southern Sierra Madre in Wyoming south through Utah and Colorado into northeastern Arizona (Karlstrom and others, 1987, fig. 1). These rocks constitute an accretionary terrane that Reed and others (1987) called the Colorado province. The metamorphic rocks of the Colorado province in the Sierra Madre and Colorado are derived from sedimentary and volcanic rocks. The metasedimentary rocks include biotite gneiss, schist, and migmatite, with subordinate hornblende gneiss, calc-silicate rock, marble, metagraywacke, and quartzite; the metavolcanic rocks include quartz-feldspar gneiss (metatuff), greenstone, and amphibolite (Tweto, 1980a; Reed and others, 1987). In Utah, 1.7-billion-year-old metamorphic rocks exposed in canyons of the Colorado and Dolores Rivers northeast of Moab include biotite gneiss and schist, hornblende schist, and migmatite (Dane, 1935, p. 22–23; Hintze, 1973, p. 157–158). In the Grand Canyon of northeastern Arizona, metamorphic rocks of Colorado province age (1.65 billion years) are assigned to the Vishnu Schist (fig. 2). As described by Billingsley and others (1987, p. 20), the Vishnu Schist consists of amphibolite, hornblende schist, anthophyllite-cordierite schist, sillimanite-bearing quartz-feldspar schist, and migmatite gneiss.

In the Colorado province of Colorado and Wyoming, the metamorphic rocks are invaded by calc-alkaline plutons that collectively constitute nearly half of the Early Proterozoic terrane (Reed and others, 1987, p. 861). Plutons of variably foliated monzonitic granite, granodiorite, and tonalite are the most widespread, but small plutons, dikes, and sills of gabbro, diabase, quartz diorite, and trondhjemite occur (Reed and others, 1987, p. 861). According to Hedge and others (1986, pl. 1), the Early Proterozoic plutonic rocks of Colorado and Wyoming were emplaced 1.6 to 1.7 billion years ago. In the Grand Canyon, the Vishnu Schist is intruded by the Zoroaster Plutonic Complex of foliated and nonfoliated granitic plutons, some of which postdate the metamorphism (Billingsley and others, 1987, p. 22).

Considerably less metamorphosed than the Early Proterozoic rocks, sedimentary rocks of the Uncompahgre Formation in and near the San Juan Mountains of southwestern Colorado and unnamed slightly metamorphosed, sedimentary and volcanic rocks exposed in the Defiance Plateau of Arizona apparently were deposited in a marine setting after the tectonic events that deformed and metamorphosed the Early Proterozoic rocks. The Uncompahgre Formation is an 8,000-ft-thick sequence of crossbedded quartzite (fig. 3), conglomerate, slate, and phyllite (Hedge and others, 1986, p. 10). The Defiance Plateau sequence consists of quartzite, phyllite, schist, silicified limestone, and greenstone (Cooley and others, 1969, p. 10–11). The age of the Uncompahgre Formation is constrained by dated rocks beneath it and by the cross-cutting Eolus Granite as between 1.6 and 1.45 billion years (Hedge and others, 1986, p. 10). Thus, the Uncompahgre Formation is considered Early and Middle Proterozoic.

Middle Proterozoic history apparently was dominated by the emplacement of granitic and monzonitic plutons throughout the UCRB. These plutons, which range from 1.48 to 1.35 billion years old, include the Sherman Granite in the Sierra Madre, the Silver Plume Granite in the Front Range, the St. Kevin Granite in the Sawatch Range, the Eolus Granite in the San Juan Mountains, quartz monzonite intrusives in the Uncompahgre Plateau and Paradox Basin, and nonfoliated granitic plutons in the Zoroaster Plutonic Complex of the Grand Canyon (Hintze, 1973, p. 157–158; Hedge and others, 1986, pl. 1; Billingsley and others, 1987, p. 22).

The Precambrian culminated with mild tectonic and igneous activity, accompanied by the deposition of sedimentary rocks between about 1.2 billion and 800 million years ago. These sedimentary rocks have not been metamorphosed. Igneous rocks include the 1-billion-year-old Pikes Peak Granite in the Front Range of Colorado (Hedge and others, 1986, pl. 1) and the 1.1-billion-year-old Cardenas Lavas (the top of the Unkar Group) in the Grand Canyon (Beus and Lucchita, 1987, p. 13). The latest sedimentary deposits of Proterozoic age include the Uinta Mountain Group in the Uinta Mountains and vicinity and the Grand Canyon Supergroup in the Grand Canyon area.

Sedimentary rocks of the Uinta Mountain Group (Wallace and Crittenden, 1969) unconformably overlie the Archean Red Creek Quartzite in the Uinta Mountains and are encountered in boreholes in the Uinta, Piceance, and Sand Wash Basins (pl. 4). The majority of this unit consists of red, gray, pink, and white quartzite and arkosic sandstone with lenses and interbeds of red and olive-green argillite and fissile shale (fig. 4). In the western Uinta Mountains and Uinta Basin, the quartzite and sandstone

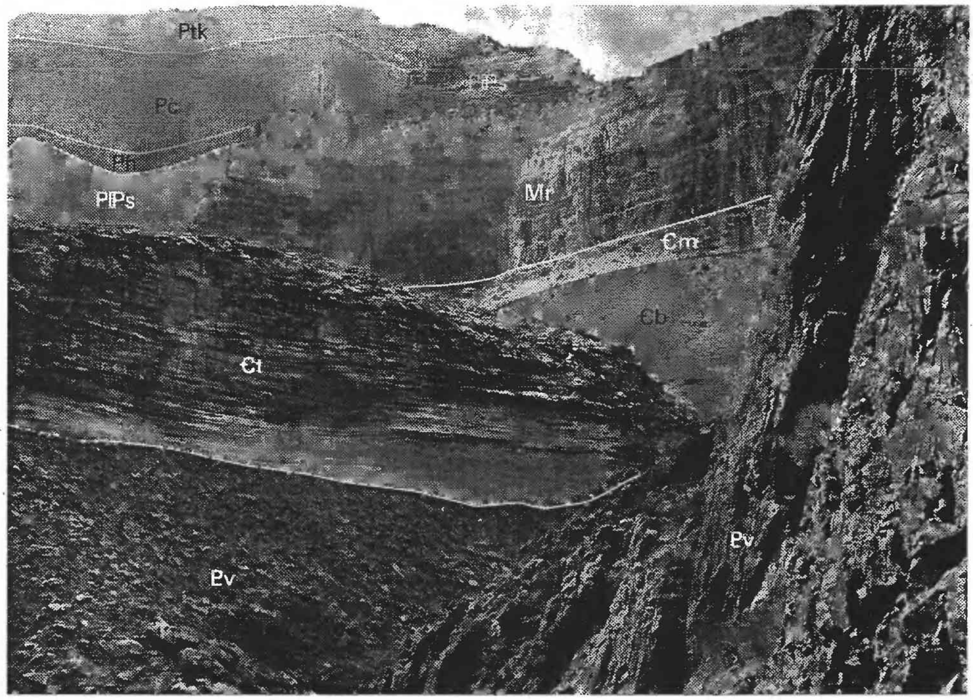



FIGURE 2.—Rocks ranging in age from Proterozoic to Permian exposed along the Colorado River in the Grand Canyon, Ariz. Ꝑv, Proterozoic Vishnu Schist; Єt, Cambrian Tapeats Sandstone; Єb, Cambrian Bright Angel Shale; Єm, Cambrian Muav Limestone; Mr, Mississippian Redwall Limestone; PIPs, Pennsylvanian and Permian Supai Group; Ph, Permian Hermit Shale; Pc, Permian Coconino Sandstone; Ptk, Permian Toroweap Formation and Kaibab Formation.

are overlain by as much as 5,000 ft of olive-green and black siltstone and claystone with quartzite and arkosic sandstone interbeds, that constitute the Red Pine Shale. The Uinta Mountain Group is as much as 24,000 ft thick in the Uinta Mountains (Hansen, 1965b, p. 32–38). As indicated by intrusive rocks and the age of the Red Pine Shale, the Uinta Mountain Group probably was deposited between 1,440 and 950 billion years ago (Hedge and others, 1986, p. 10).

The 13,000-ft-thick Grand Canyon Supergroup consists of the Unkar Group, Nankoweap Formation, and Chuar Group (Beus and Lucchita, 1987, p. 10). The Unkar Group, which was deposited between 1.25 and 1.1 billion years ago (Donald Elston, U.S. Geological Survey, oral commun., 1987), includes the Bass Limestone, Hakatai Shale, Shinumo Quartzite, interbedded sandstone, siltstone, and mudstone of the Dox Formation, and the Cardenas Lavas. The Nankoweap Formation consists mostly of sandstone and conglomerate. The Chuar Group, which was deposited between 1,070 and 820 million years ago (Beus and Lucchita, 1987, p. 12), is composed of shale and interbedded limestone of the Galeros and Kwagunt Formations overlain by interbedded sandstone, conglomerate, and breccia of the Sixty Mile Formation. The Grand Canyon Supergroup apparently was removed by erosion north and east of the Paria River (pl. 4), and its exact thickness between the Grand Canyon and Paria River is unknown.

## GENERAL PALEOZOIC STRATIGRAPHY

Formations representing all Paleozoic systems, except the Silurian, are present in the study area (table 1). As evidenced by limestone inclusions of Silurian age in kimberlite diatremes along the Colorado-Wyoming border (Ross and Tweto, 1980, p. 52–53), Silurian marine deposits probably were present at one time but have since been removed by erosion. Paleozoic rocks of the UCRB were deposited during five major marine incursions.

Formations of Cambrian to Mississippian age (pl. 5) predominantly consist of marine carbonate rocks and are relatively thin when compared to overlying formations of mostly Pennsylvanian and Permian age (some of these formations are partly Mississippian or partly Triassic). Formations of Cambrian age comprise a transgressive marine sequence of sandstone, shale, and carbonate rocks. (In this report, the term "shale" includes claystone, mudstone, siltstone, sandy shale, carbonaceous shale, marl, and argillite.) Formations of Ordovician age consist mostly of limestone and dolomite, with a thin intervening sandstone unit present locally. The Ordovician rocks formerly covered a much larger area, but, because of erosion, are now restricted to northwestern Colorado and the northwestern Green River Basin and adjacent areas in Wyoming. Formations of Devonian age consist of a lower mixed carbonate-shale-sandstone sequence and an upper limestone-dolomite sequence. Formations of Mississippian age consist mostly of a thick carbonate sequence that locally is capped by a thin sequence of variable carbonate, shale, and sandstone lithology. Formations of Cambrian to Mississippian age generally are less than 4,500 ft thick, but they are as much as 5,500 ft thick in the High Plateaus region of Utah and 6,500 ft thick in the Overthrust Belt of Wyoming.

Formations of mostly Pennsylvanian and Permian age predominantly consist of terrigenous or marine sandstone and

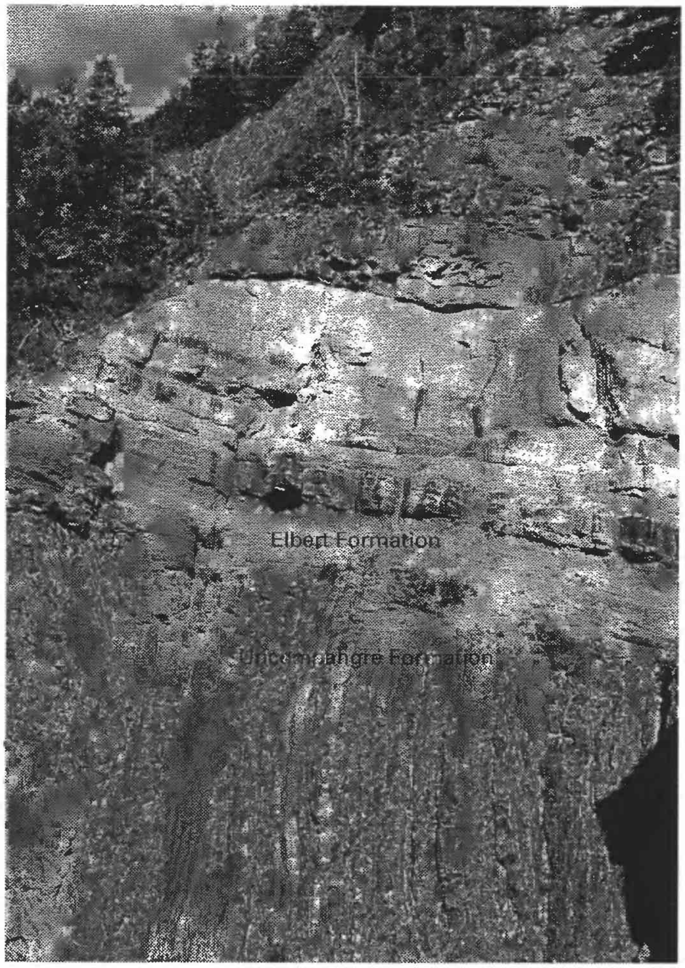



FIGURE 3.—Near-vertical beds of quartzite in the Early and Middle Proterozoic Uncompahgre Formation overlain by subhorizontal dolomite, shale, and sandstone of the Devonian Elbert Formation at Box Canyon Falls, Ouray, Colo.

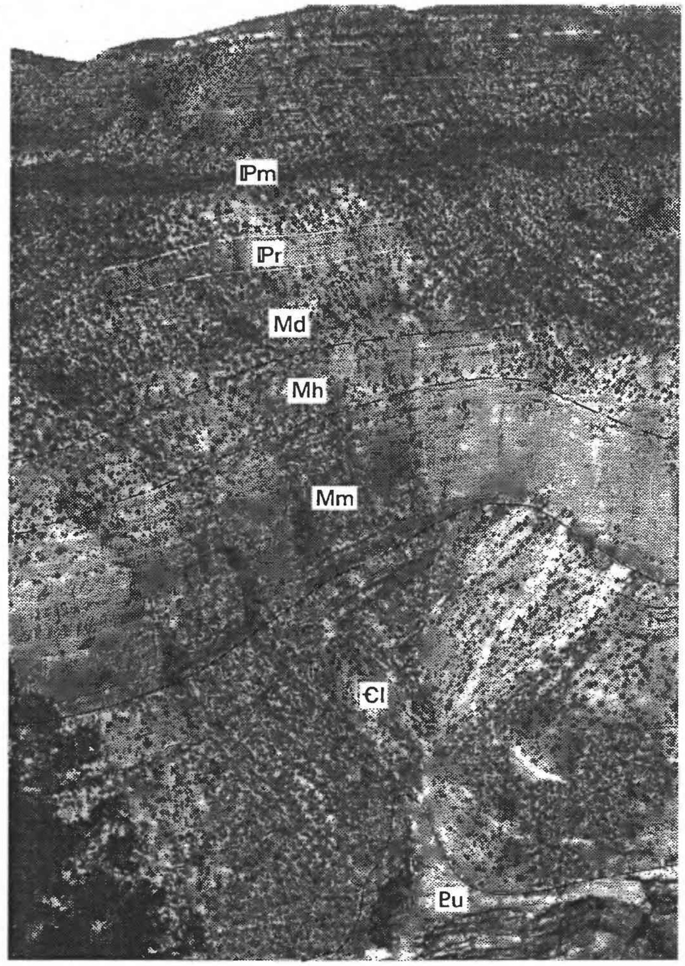



FIGURE 4.—Rocks ranging in age from Proterozoic to Pennsylvanian exposed along the Green River at the eastern end of the Uinta Mountains in Dinosaur National Monument, Colo. Units shown are Pu, Proterozoic Uinta Mountain Group; €l, Cambrian Lodore Formation; Mm, Mississippian Madison Limestone; Mh, Mississippian Humbug Formation; Md, Mississippian Doughnut Shale; IPr, Pennsylvanian Round Valley Limestone; and IPm, Pennsylvanian Morgan Formation. The shaly upper part of the Lodore Formation is equivalent to the Gros Ventre Formation of Wyoming and the Ophir Shale of the western Uinta Mountains and southeastern Utah.

shale. The basal sequence in this interval, of Mississippian and Pennsylvanian age, consists of partly marine and partly terrigenous shale with subordinate interbeds of limestone and dolomite. Formations of Pennsylvanian age predominantly consist of interbedded carbonate rocks, sandstone, and shale of marine origin. However, thick sequences of marine evaporites are present in the Paradox and Eagle Basins, and thick terrigenous deposits of sandstone, shale, and conglomerate are present in northwestern Colorado. Formations of Pennsylvanian and Permian age predominantly consist of partly marine and partly eolian sandstone and terrigenous red beds of variable shale, sandstone, and conglomerate. Formations of Permian age predominantly consist of interbedded carbonate rocks, sandstone, and shale of marine origin and locally contain interbedded anhydrite. Formations of Permian and Triassic age consist of terrigenous red beds with minor to subordinate carbonate rocks and gypsum-anhydrite.

Formations of mostly Pennsylvanian and Permian age are characterized by abrupt changes in facies. Nomenclatural variation from area to area is based on arbitrary groupings of stratigraphic sequences. The total thickness of these rocks generally is less than 2,000 ft in Wyoming and less than 4,000 ft elsewhere. However, these rocks are as much as 10,500 ft thick in the Paradox basin and 17,500 ft thick in the Elk Mountains.

The total thickness of the Paleozoic rocks ranges from 0 to about 18,000 ft (pl. 3). The Paleozoic rocks are missing in the center of the Uinta Mountains, Uncompahgre Plateau, Sawatch Range, Park Range, Gore Range, and Front Range (see pl. 1 for locations of geographic areas discussed in this paragraph) because of erosion or nondeposition. Thicknesses increase generally westward, reflecting repeated marine incursions from the west throughout the Paleozoic. However, depositional centers on the eastern side of the area occur. Thicknesses of 8,000–16,000 ft in the Paradox Basin and 8,000–18,000 ft in the Eagle Basin–Elk Mountains area are the combined result of evaporite flowage and the deposition of large volumes of terrigenous material derived from the ancestral Rocky Mountains (of Pennsylvanian and Permian age). On the western side of the UCRB, maximum thicknesses generally range from 7,000 to 8,000 ft. Thicknesses in the Overthrust Belt of Wyoming are allochthonous; Paleozoic rocks present in the area were deposited in foreland basins of the Cordilleran miogeosyncline 50–60 miles to the west (Royse and others, 1975; Peterson, 1977).

Paleozoic rocks are more than 25,000 ft deep in several structural basins but less than 2,500 ft deep in and near uplifted areas (pl. 3). Abrupt changes in the thickness of the overlying Mesozoic and Tertiary rocks occur on the western edge of the Wind River Mountains, on the eastern edge of the Overthrust Belt, and on the northern and southern edges of the Uinta Mountains because of thrust faults. Paleozoic rocks are 26,000–27,000 ft deep in parts of the Green River, Great Divide, Washakie, and Uinta Basins; 15,000–22,000 ft deep in parts of the Sand Wash and Piceance Basins, and the High Plateaus region; 5,000–10,000 ft deep in parts of the Henry Mountains, Kaiparowits, and Kaibito Basins, the Douglas Creek Arch, and the Rock Springs Uplift; and generally less than 5,000 ft deep elsewhere. The Paleozoic rocks are less than 2,500 ft deep in large parts of the area south of the Uncompahgre Plateau and east of the Colorado and Green Rivers. They also generally are less than 2,500 ft deep in the White River Plateau, Elk Mountains, and Eagle Basin, where they form most of the land surface.

## MESOZOIC ROCKS

Paleozoic rocks in the study area are overlain nearly everywhere by rocks of Triassic age (pl. 4). Lower Triassic rocks comprise the base of the Triassic System in most areas. However, these rocks were either eroded or never deposited east of the Monument Upwarp and northwestern Paradox Basin and south of the southern Piceance Basin and Elk Mountains. In most of this area, Upper Triassic rocks form the base of the Triassic System. The Upper Triassic rocks are missing in an area encompassing the southeastern corner of the Piceance Basin, eastern West Elk Mountains, and western Elk Mountains and in a small part of the southern Gore Range. In these areas, largely eolian rocks of Jurassic age, either the Wingate Sandstone or Entrada Sandstone (see Peterson, 1988, for detailed stratigraphic discussion of Jurassic rocks in the southern Rocky Mountain region) overlie the Paleozoic rocks. Triassic rocks also are missing in some areas of the Wyoming Overthrust Belt where the Wasatch Formation, a unit of Tertiary age mostly consisting of shale and fine-grained sandstone (see Oriel, 1969, for detailed description of the Wasatch Formation at the eastern edge of the Overthrust Belt), caps the Paleozoic rocks.

Lower Triassic rocks in contact with Paleozoic rocks in the study area include the Moenkopi Formation, Woodside Shale, upper part of the State Bridge Formation, upper part of the Goose Egg Formation, and Dinwoody Formation (see Hansen, 1965b, and Stewart and others, 1972a, for detailed descriptions). Upper Triassic rocks in contact with Paleozoic rocks in the study area include the Chinle and Dolores Formations (see Stewart and others, 1972b, for detailed descriptions).

The Moenkopi Formation is divided into numerous members on the basis of lithologic variations that do not persist throughout the region. Although shale is the predominant lithology, sandstone, conglomerate, and carbonate rocks also are present in the formation.

In northeastern Arizona and southeastern Utah west of the Monument Upwarp and south of the Capitol Reef Fold and Fault Belt (pl. 1), members of the Moenkopi Formation in contact with Paleozoic rocks are lithologically diverse. The Timpoweap Member consists of a laterally variable sequence of gray and yellow limestone, siltstone, sandstone, and chert-pebble conglomerate. The Sinbad Limestone Member consists of yellowish-gray, olive-gray, and yellowish-orange limestone and dolomite with siltstone interbeds. The lower red member consists mostly of grayish-red and light-brown, micaceous siltstone. The ledge-forming member consists of grayish-red, reddish-brown, orange, and gray siltstone, sandy siltstone, and very fine grained sandstone.

In the Defiance Plateau, Monument Upwarp, and northwestern Paradox Basin, the Moenkopi Formation, in contact with Paleozoic rocks, mostly consists of siltstone, sandstone, and conglomerate. The lower massive sandstone member consists of grayish-yellow, very fine grained sandstone. The Hoskinnini Member consists of reddish-brown sandy siltstone and silty, very fine grained sandstone. The Tenderfoot Member consists of reddish-brown siltstone and conglomerate with interbedded gypsum near the bottom of the unit.

In most of southeastern Utah where the Moenkopi Formation is the basal Triassic unit, the lower slope-forming member overlies the Paleozoic rocks. The lower slope-forming member consists of grayish-red, yellowish-gray, and light-greenish-gray siltstone and sandy siltstone. The equivalent of this unit in northwestern Colorado, the eastern Uinta Mountains, and the southeastern Washakie Basin is the undivided Moenkopi Formation. The undivided Moenkopi Formation consists of red, brown, orange, yellow, and gray siltstone with minor amounts of mudstone, very fine grained sandstone, and gypsum.

Stratigraphic equivalents of the Moenkopi Formation are composed mostly of shale. The Woodside Shale, in the Uinta Basin and western Uinta Mountains, consists of red siltstone and claystone with some interbeds of very fine grained sandstone. The upper part of the State Bridge Formation from the Piceance Basin and White River Plateau to the Park Range consists of red siltstone with subordinate claystone and sandstone layers. The upper part of the Goose Egg Formation in the eastern Sand Wash, Washakie, and Great Divide Basins consists of red anhydritic and dolomitic shale (the Freezeout Shale Member) capped by a thin limestone bed (the Little Medicine Member). The Dinwoody Formation consists of light-gray and greenish-gray limy siltstone and claystone with interbedded friable, fine-grained sandstone, crystalline limestone and dolomite, and minor gypsum.

In many areas, Upper Triassic rocks in contact with Paleozoic rocks predominantly consist of sandstone and conglomerate. The Shinarump Member of the Chinle Formation, which overlies the Paleozoic rocks in the Defiance Plateau area, consists of yellowish-gray and yellow-orange, friable, fine- to coarse-grained sandstone and chert-pebble conglomerate. The Moss Back Member of the Chinle Formation and the lower member of the Dolores Formation, which form the basal Triassic sequence in the Paradox Basin and San Juan Mountains, are very similar to the Shinarump Member. The Gartra Member of the Chinle Formation, which caps the Paleozoic rocks in a small area southwest of Glenwood Springs, Colo., also is composed of sandstone and conglomerate.

Shale members of the Chinle Formation overlie Paleozoic rocks in three areas. On the north flank of the Uncompahgre Plateau, the Paleozoic rocks are overlain by the Church Rock Member and red siltstone member of the Chinle Formation. The Church Rock Member is composed of reddish-brown, reddish-orange, and light-brown siltstone with lenses and persistent beds of pink and light-greenish-gray fine-grained sandstone and sandy siltstone. The red siltstone member in this area consists of reddish-brown and grayish-red siltstone with lenses of limestone-pebble conglomerate. South of the Uncompahgre Plateau, near Placerville, Colo., the red siltstone member again overlies Paleozoic rocks. In this area, however, the unit contains a large proportion of red, fine-grained sandstone interbedded with the siltstone. In the Four Corners area, Paleozoic rocks are overlain by the Petrified Forest Member of the Chinle Formation. The Petrified Forest Member consists of red, greenish-gray, purple, yellow, and blue claystone, clayey siltstone, and clayey sandstone with lenses of coarse-grained sandstone and conglomerate.

## STRUCTURE

The UCRB is situated in an unstable foreland region between the stable North American Craton to the east (Great Plains physiographic province) and the block-faulted Cordilleran Geosyncline to the west and south (Basin and Range physiographic province). Tectonic activity in the UCRB began in the Precambrian, continued repeatedly throughout the Paleozoic, and culminated on a regional scale in the Tertiary (Grose, 1972; Kent, 1972; Hintze, 1973; Peterson, 1977; Stone, 1977, 1986; Tweto, 1980c; De Voto and others, 1986; Hansen, 1986a).

The Paleozoic rocks in the UCRB have been deformed into numerous synclines and anticlines (pl. 1). Many mountain ranges, including the Wind River Mountains, Gros Ventre Range, Uinta Mountains, San Juan Mountains, Front Range, and Sawatch Range, essentially are large anticlinoriums with Precambrian cores and limbs composed of folded and faulted Paleozoic, Mesozoic, and Tertiary sedimentary rocks (see sections *B–B′*, *D–D′*, and *G–G′*, pl. 2). Many of the basins and uplifts, particularly in the Colorado Plateaus province, are distinctly asymmetrical. Such folds, including those forming the White River Plateau, Piceance Basin, Uinta Basin, San Rafael Swell, Circle Cliffs Uplift, Henry Mountains Basin, Monument Upwarp, and Kaibab Plateau, are steep to overturned on one limb and gently homoclinal on the opposite limb (see sections *B–B′*, *D–D′*, *E–E′*, and *H–H′*, pl. 2). Some folds, such as those forming the Rock Springs Uplift, Rawlins Uplift, Douglas Creek Arch, and Defiance Plateau, are nearly symmetrical (see sections *D–D′* and *I–I′*, pl. 2).

Most major fold axes trend northwesterly or north-northeasterly. The Uinta Mountains, however, consist of two domes with the longer axes aligned approximately east-west (pl. 1). The two domes formed by the intersection of an east-west-oriented anticline with the axes of the previously uplifted Moxa Arch on the west and the Rock Springs Uplift–Douglas Creek Arch structural trend on the east (Ritzma, 1969; Hansen, 1986a). According to Hansen (1986b, p. 40), uplift began during latest Cretaceous time, reached its peak from Paleocene to Oligocene time, and continued into the Quaternary with large-scale tilting of the eastern Uinta Mountains and both normal and reverse movement along new and preexisting faults.

Domes of small areal extent that resulted from the intrusion of Tertiary igneous rocks occur in the southern part of the Colorado Plateaus province (see pls. 1 and 2). These domes form the San Juan Mountains (including the outlying San Miguel, Rico, and La Plata Mountains), the Abajo Mountains, the Henry Mountains, Navajo Mountain, Sleeping Ute Mountain, the Carrizo Mountains, and La Sal Mountains.

Faults are associated with most uplifts (pl. 1). The most prevalent faults are high-angle, reverse, or normal faults (Grose, 1972, p. 36). High-angle normal faults transect most ranges in the Southern and Middle Rocky Mountains provinces and are the dominant type of fault in the Colorado Plateaus province. High-angle normal faults, arranged en echelon, border the Gore Range, Sawatch Range, Uncompahgre Plateau, Gunnison Plateau, and the High Plateaus of Utah (see sections *D–D′*, *E–E′*, *F–F′*, and *H–H′*, pl. 2). The Uncompahgre Plateau essentially is a horst over which Mesozoic rocks are drape-folded (Stone, 1977; Heyman and others, 1986). A prominent zone of faulting known as the Colorado Lineament (Warner, 1980) extends northeastward from northern Arizona to the Southern Rocky Mountains and includes the Needles Fault Zone of the Canyonlands region and the Homestake Shear Zone of the Sawatch Range (pl. 1).

One of the most complex structural features in the UCRB is the Paradox Basin (fig. 5), an area characterized by northwest-trending anticlines, synclines, and high-angle faults. The

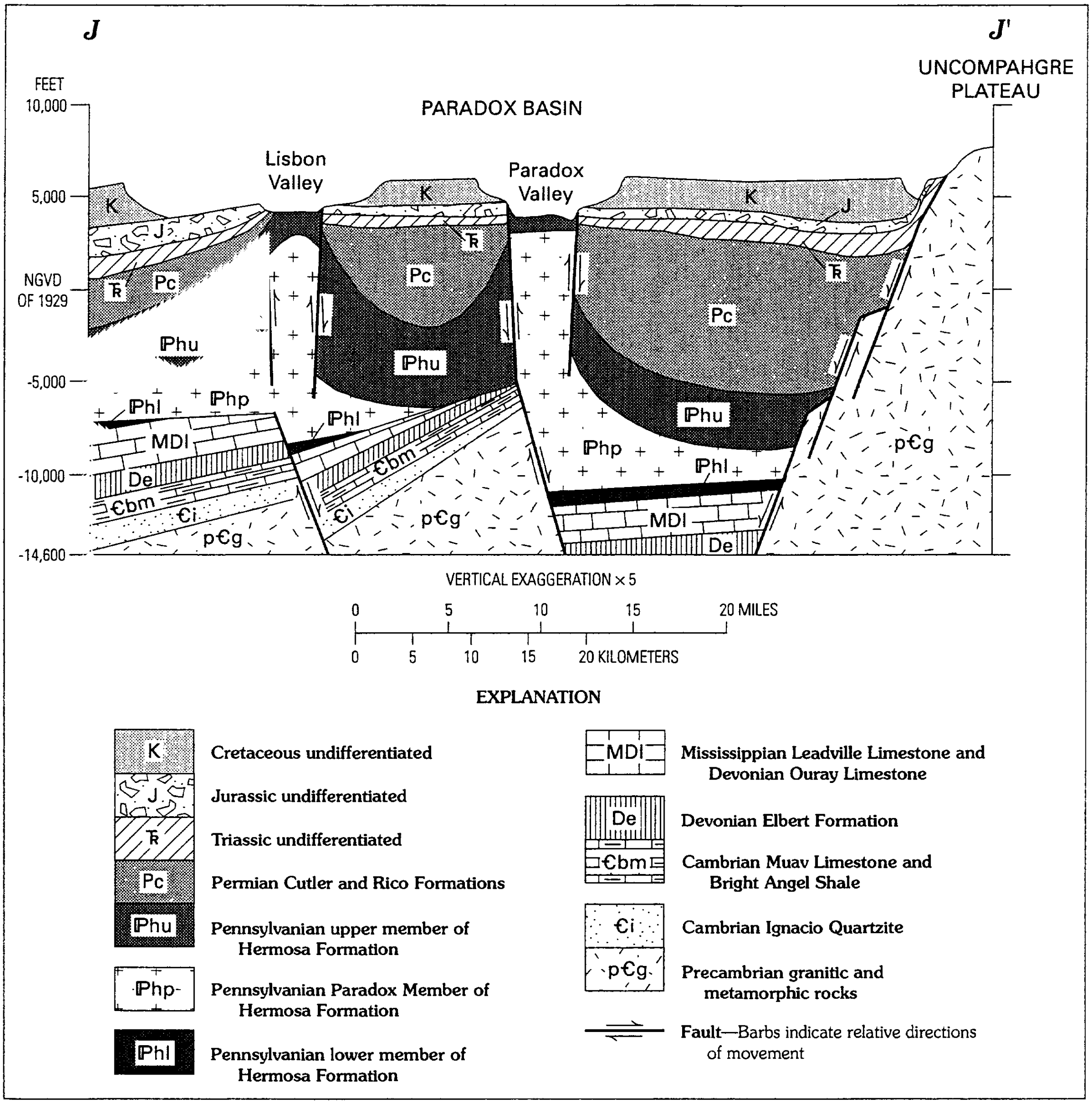



FIGURE 5.–Geologic section showing deformational styles in the Paradox Basin, Colo. Modified from Baars (1983, p. 73); location of section shown on plate 2.

anticlines were formed by the mobilization and intrusion of salt in the Hermosa Formation as thousands of feet of Cutler Formation sediments were being eroded from the rising Uncompahgre Plateau (Baars, 1983, p. 59–78). Consequently, deformation decreases in intensity away from the Uncompahgre Plateau as the thickness of the Cutler Formation decreases (Kelley, 1958, p. 31). The salt-cored anticlines are arranged en echelon into five systems (pl. 1). At the crests of the anticlines are grabens that formed by the collapse of the salt cores and overlying sediments in response to salt solution (Shoemaker and others, 1958). The collapse breccia, known locally as cap rock, floors prominent flat-bottomed valleys sparsely covered with Quaternary alluvium.

Thrust faults border the west and south sides of most uplifted areas in the Southern and Middle Rocky Mountains and Wyoming Basin provinces. Thrust faults bordering the Wind River, Gros Ventre, Uinta, and Elk Mountains, the Front and Park Ranges, the Sierra Madre, the White River Plateau, and the Rock Springs and Rawlins Uplifts can have as much as 40,000 ft of stratigraphic displacement (see sections *A–A′*, *B–B′*, and *C–C′*, pl. 2). Paleozoic and Mesozoic rocks in the lower plate of the Wind River Fault (section *A–A′*, pl. 2) may extend to the crest of the Wind River Mountains beneath outcropping Precambrian rocks. Similarly, Paleozoic rocks in the lower plate of the Uinta-Sparks Fault (pl. 1) extend beneath the Precambrian (Proterozoic) Uinta Mountain Group on the north flank of the eastern Uinta Mountains (fig. 6).

In contrast to these "thick-skinned" thrusts, thrust faults in the Overthrust Belt typically do not extend into the

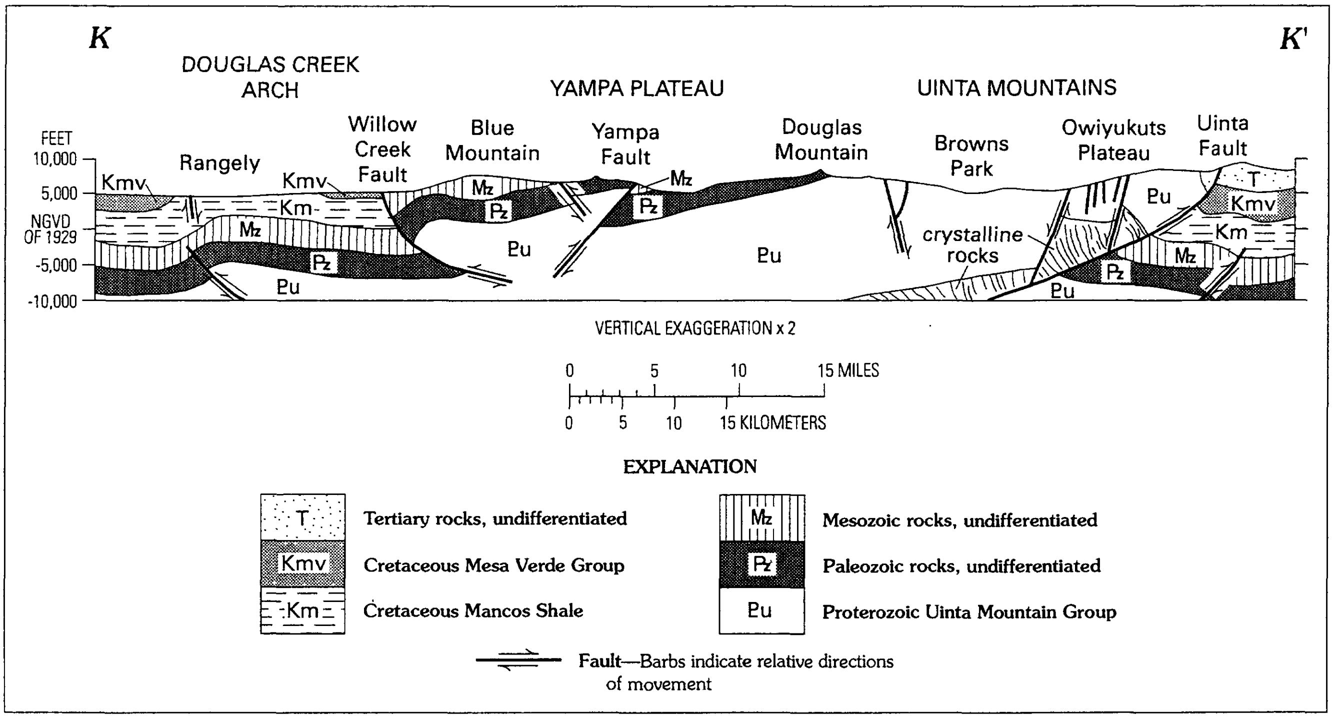



FIGURE 6.—Geologic section showing deformational styles in the Uinta Mountains in northwestern Colorado. Modified from Hansen (1986a, fig. 3); location of section shown on plate 2.

Precambrian basement (see section *A–A′*, pl. 2). Detachment typically occurs within Cambrian shale and carbonate layers but also occurs within Triassic, Jurassic, and Cretaceous shale layers (Royse and others, 1975, p. 44). Stratigraphic throw on each of the major thrust faults is about 20,000 ft (Armstrong and Oriel, 1965, p. 1857), but numerous imbricate thrust faults with smaller throw are present in the hanging walls of the major thrusts (see, for example, Royse and others, 1975, pls. 1 and 2). From west to east, the major thrust faults in Wyoming are the Tunp, Absaroka, Darby-Hogsback, and Jackson-Prospect; in Utah, the leading edge of the Overthrust Belt is marked by the Charleston Thrust Fault (pl. 1). Asymmetric folds and Basin and Range-style, high-angle, normal faults occur in the hanging walls of the major thrusts (Blackstone, 1977, p. 374–375). Typical of these younger faults is the Hoback Fault bordering the west side of the Hoback Range (pl. 1).

Large parts of the UCRB contain no visible faults of appreciable length. Small outcrops of lower and middle Paleozoic rocks in the Green River Basin northwest of Pinedale, Wyo. (pl. 2), may be the remnants of a gravity-slide block from the Wind River Mountains to the east. Other than this structure and small faults concentrated around the crests of intervening arches, few large faults are known in the Green River, Great Divide, Washakie, Sand Wash, Piceance, and Uinta Basins. Similarly, much of the area between the San Rafael Swell and Circle Cliffs Uplift on the west and the Paradox Basin on the east virtually is free of faults. Notable exceptions are the Needles Fault Zone (which controls the course of the Colorado River through the area), grabens bordering the Abajo Mountains Dome, and a zone of north-trending faults between the Colorado and San Juan Rivers in the southwestern part of the Monument Upwarp.

## STRATIGRAPHY OF PALEOZOIC HYDROGEOLOGIC UNITS AND RELATED ROCKS

Eleven hydrogeologic units consisting of Paleozoic rocks have been designated in the study area. In this section of the report, lateral variations in stratigraphic nomenclature, thickness, and lithology within each hydrogeologic unit are discussed in detail. Contacts between geologic units at the tops and bottoms of the hydrogeologic units also are discussed, in order to show how the hydrogeologic units relate to each other. Paleontologic discussion is minimized in keeping with the hydrogeologic emphasis of the UCRB-RASA; for more thorough discussions of the paleontology, numerous references are given throughout the remainder of the report. Hydrogeologic units from the Flathead aquifer to the Madison aquifer (table 1) are considered to transmit ground water as a composite aquifer system, the Four Corners aquifer system. Substantial discussion of this aquifer system is contained in Professional Paper 1411–B (Geldon, in press).

## FLATHEAD AQUIFER

The Flathead aquifer (pl. 6) is composed of beach and littoral sediments deposited during the initial advance of the Paleozoic seas across the region (Kent, 1972; Lochman-Balk, 1972). Component geologic units include the Flathead Sandstone, lower part of the Lodore Formation, Sawatch Quartzite, Ignacio Quartzite, Tapeats Sandstone, Tintic Quartzite, and unnamed equivalents (table 1 and pl. 5). These formations become progressively younger from west to east across the region in the direction of marine advance (fig. 7). On the western side of the region, the component formations are Lower to Middle Cambrian (Noble, 1922, p. 38–39; Foster, 1947, p. 1548; Anderman, 1956, p. 50; Baker, 1976); on the eastern side, component formations are Middle to Upper Cambrian (Thomas, 1951, p. 32–33; Baars, 1958, p. 95–97; Keefer and Van Lieu, 1966, p. 14–15; Tweto and Lovering, 1977, p. 15).

The Flathead aquifer thickens toward depositional centers in the Uinta Basin, Overthrust Belt, southwestern Colorado, and northeastern Arizona (pl. 6). Its maximum thickness within the UCRB currently is estimated from borehole data to be about 800 ft. However, measured sections in the Wasatch Range, 18–27 mi west of the UCRB (Baker and Crittenden, 1961; Baker, 1973) indicate that the Flathead aquifer may be as much as 1,200–1,300 ft thick in Wyoming. Thinned by erosion or nondeposition, the aquifer is missing in the center and on the north flank of the Uinta Mountains, east of the Sand Wash and Eagle Basins, in the Uncompahgre Plateau and southern Piceance Basin, and in much of the Defiance Plateau and Four Corners area. The aquifer is at or near the surface of the flanks of uplifted areas, but it typically is 7,000–34,000 ft deep in structural basins (pl. 7).

### COMPONENT GEOLOGIC UNITS

The Flathead aquifer in southwestern Wyoming consists of the Flathead Sandstone. In the Gros Ventre Range, the Flathead Sandstone is composed of white, gray, tan, and maroon, fine- to medium-grained, crossbedded sandstone and quartzite with a basal interval of quartz-pebble conglomerate and partings of green, micaceous shale in upper layers (Foster, 1947, p. 1544; Simons and others, 1988, p. 8). Similarly, the Flathead Sandstone in the Wind River Mountains consists of pink, reddish-brown, tan, and gray laminated, fine- to coarse-grained sandstone overlying an arkosic-pebble conglomerate. Most of the sandstone layers in the Wind River Mountains are quartzitic, some are glauconitic or hematitic, and upper layers contain partings of green and grayish-green, micaceous shale (Keefer and Van Lieu, 1966, p. 14–15). In the Rawlins area, the Flathead Sandstone (fig. 8) consists of a basal interval of arkosic conglomerate, a middle interval of light-gray and pink quartzitic sandstone, and an upper interval

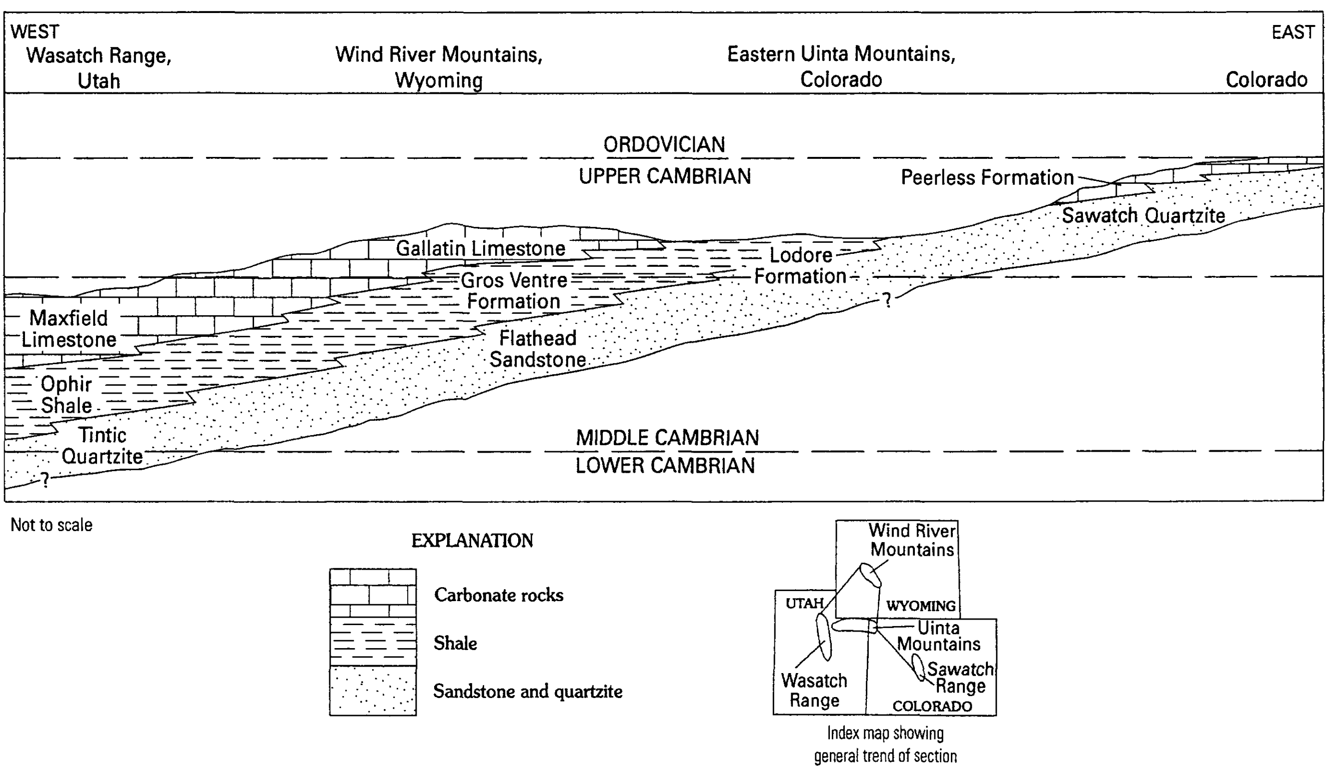



FIGURE 7.—Schematic section showing time transgression and intertonguing of facies in the Cambrian sedimentary rocks of Wyoming, Utah, and Colorado. Baars (1983, p. 54) showed similar stratigraphic relations and time transgression in the Cambrian rocks between the Grand Canyon area of Arizona and the San Juan Mountains of southwestern Colorado.

FIGURE 8.—Cambrian Flathead Sandstone at Rawlins, Wyo.

of red and purplish-gray, friable to quartzitic, medium-grained sandstone (Berry, 1960, p. 70–71).

Similar to the Flathead Sandstone, the Lodore Formation at Cross Mountain consists of white, orange, and yellow quartzite, quartzitic sandstone, and glauconitic sandstone with shale partings near the top (Wilson, 1957). To the west, in Dinosaur National Monument, this sandstone interval grades into gray, pale-green, and pink, medium- to coarse-grained, pebbly sandstone overlain by an interval predominantly consisting of shale (Hansen and others, 1983). Both the sandstone and shale intervals are included in the Lodore Formation, despite their contrasting lithologies (Untermann and Untermann, 1954). Because the upper (shaly) interval contains an Upper Cambrian fauna, the entire Lodore Formation traditionally has been considered Upper Cambrian. However, the lower and thicker (sandy) part of the formation is unfossiliferous, and its age realistically cannot be established unequivocally. In this report, the upper (shaly) part of the Lodore Formation is considered to be equivalent to the Gros Ventre Formation, on the basis of both lithology and fossils, and is included with the Gros Ventre Formation in the Gros Ventre confining unit. The lower (sandy) part of the Lodore Formation, on the basis of lithology and stratigraphic position, is inferred to be correlative with the Middle Cambrian Flathead Sandstone to the north and the Upper Cambrian Sawatch Quartzite to the south and is believed to be intermediate in age between these two formations. On the basis of this interpretation, the lower part of the Lodore Formation is included with the Flathead Sandstone and Sawatch Quartzite in the Flathead aquifer.

From the western Uinta Mountains south to the vicinity of Lake Powell, beds equivalent to the Flathead Sandstone are assigned to the Tintic Quartzite. In the Duchesne River and Lake Fork drainages of the western Uinta Mountains, the Tintic Quartzite (referred to as the Pine Valley Quartzite by Huddle and McCann, 1947b, and Huddle and others, 1951) consists of light-yellowish-brown conglomeratic sandstone overlain by massively bedded, greenish-gray sandstone (fig. 9). The sandstone layers can be calcareous, quartzitic, or arkosic, and thin to thick intervals of shale are present. In the Wasatch Range and northwestern Uinta Basin, the Tintic Quartzite consists of white, tan, and pink, fine- to medium-grained quartzite with pebbly to conglomeratic layers near the base and interbedded green shale near the top (Baker and Crittenden, 1961; Baker, 1973). Similarly, the Tintic Quartzite penetrated by boreholes in southeastern Utah consists of massively bedded, white, green, pink, and maroon, fine- to medium-grained, locally glauconitic sandstone with feldspathic, coarse-grained sandstone and conglomerate in the lower 50–70 ft and interbeds of green and red, micaceous shale in the upper part of the formation (Cooper, 1960, p. 69).

In the Piceance Basin, White River Plateau, and mountainous areas of northwestern Colorado, the equivalent of the Flathead Sandstone and Tintic Quartzite is called the Sawatch Quartzite. The Sawatch Quartzite in the southern White River Plateau (Hallgarth, 1959; Bass and Northrop, 1963) consists of light-gray, brown, and locally lavender dolomitic quartzite, quartzitic sandstone, and sandstone in beds 2–5 ft thick, with scattered layers of brown and gray dolomite and sandy dolomite and partings of light-greenish-gray shale (fig. 10). At the base is a 1- to 2-ft-thick layer of conglomeratic quartzite. A 75-ft-thick layer of dark-brown, thin-bedded glauconitic and sandy dolomite occurs 65–100 ft below the top of the formation. This

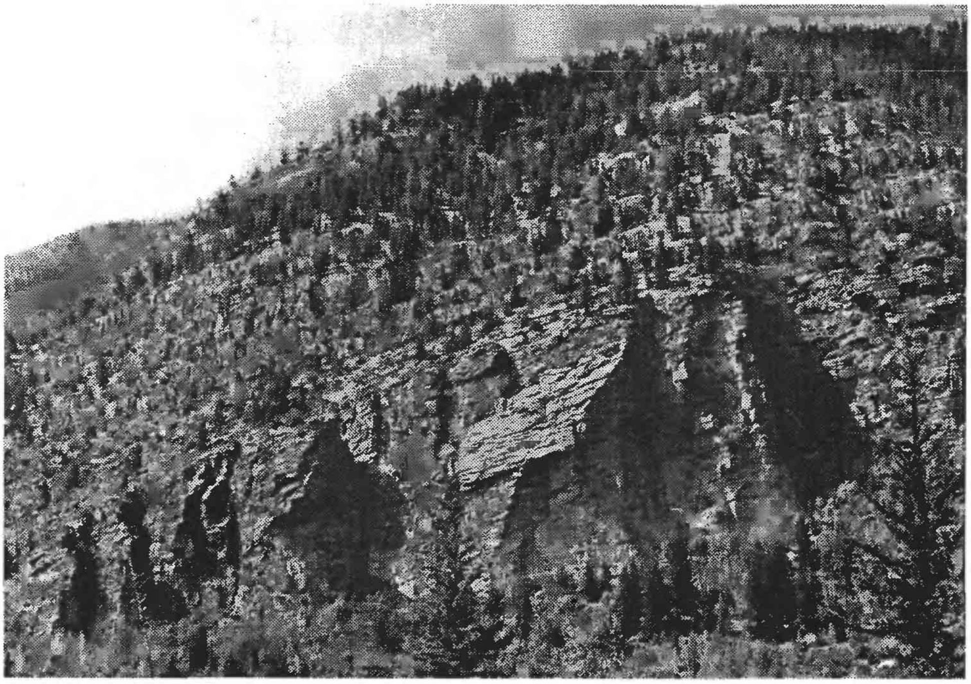


FIGURE 9.—Cambrian Tintic Quartzite at the base of a cliff on the west side of the Duchesne River, western Uinta Mountains, Utah.

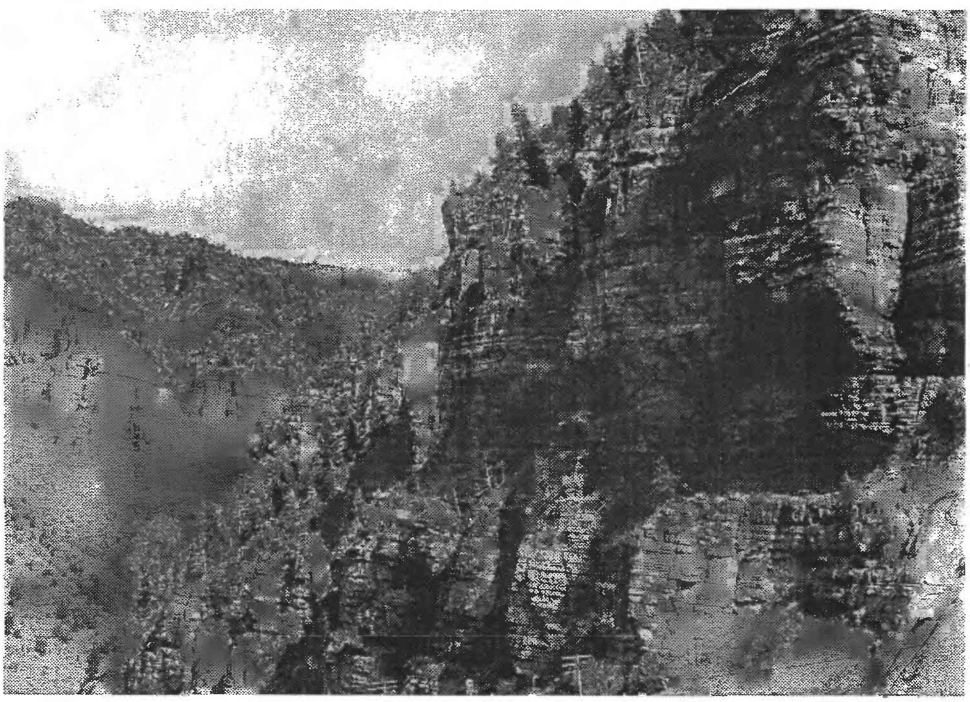


FIGURE 10.—Cambrian Sawatch Quartzite in Glenwood Canyon, Colo.

dolomitic zone persists into the northern Sawatch Range, where it is manifested as interlayered brown dolomitic sandstone and sandy dolomite (Tweto and Lovering, 1977, p. 15–19). Above and below the dolomitic zone in the northern Sawatch Range, the Sawatch Quartzite consists mostly of white, vitreous quartzite (Bryant, 1979, p. 14). In the Crested Butte area of the Elk Mountains, the Sawatch Quartzite consists of white and brown, medium- to coarse-grained sandstone; pink, red, and green, glauconitic sandstone; and white quartzite, with a thin basal conglomerate (Mallory, 1957). In the McCoy area, at the southern end of the Park Range, the Sawatch Quartzite consists of light-gray and white, quartz-pebble conglomerate and friable sandstone, with thin layers of micaceous shale near the top of the formation (Donner, 1949, p. 1218–1221).

In most of southwestern Colorado, the lateral equivalent of the Sawatch Quartzite is the Ignacio Quartzite. In the San Juan Mountains, the Ignacio Quartzite consists of massively bedded, pink and reddish quartzite overlain by white, friable to quartzitic sandstone and quartzite with shale partings (fig. 11). A basal conglomerate or conglomeratic sandstone is present locally (Baars and Knight, 1957, p. 114; Baars and others, 1987, p. 345).

In the southeastern corner of Utah and in northeastern Arizona, the Ignacio Quartzite grades into beds equivalent to the Tapeats Sandstone of the Grand Canyon area. As described by Noble (1922, p. 37–39), the Tapeats Sandstone in the Grand Canyon predominantly consists of chocolate-brown, medium- to coarse-grained sandstone (fig. 2), but the top of the formation is a thin interval of white crossbedded sandstone with green shale layers. Thin shale layers also occur from the middle to the top of the brown sandstone sequence, and lenses of quartz-pebble conglomerate occur throughout the formation. At the base of the formation is an arkosic conglomerate containing quartz pebbles and fragments of Precambrian rocks. Throughout the Grand Canyon area, the Tapeats Sandstone varies irregularly from friable to quartzitic.

## CONTACTS

Formations comprising the Flathead aquifer overlie Precambrian igneous, metamorphic, and sedimentary rocks unconformably throughout the study area. This unconformity is revealed in the Uinta Mountains only by the eastward truncation of the Red Pine Shale (Kinney, 1955, p. 23–24). In most areas, however, the Precambrian rocks are truncated noticeably by the erosional surface on which the Paleozoic rocks were deposited (Baars, 1958, p. 93; Keefer and Van Lieu, 1966, p. 14–15; Irwin and others, 1971, p. 5–6; Tweto and Lovering, 1977, p. 15; Hansen, 1986a, fig. 11). In southwestern Colorado, angular discordance between Precambrian and Paleozoic sedimentary rocks reaches extreme development and is as much as 70°–90° (Baars, 1958, p. 93). Relief on the erosional surface is barely detectable in most areas, but in the Wind River Mountains and Sawatch Range, 25–60 ft of irregularity has been observed (Richmond, 1945; Tweto, 1949, p. 160–161). In the Grand Canyon, the Precambrian terrain has a relief of as much as 900 ft, and the Tapeats Sandstone was not deposited where fault-block hills of Precambrian rocks stood as islands in the Cambrian sea (McKee, 1969, p. 42).

In contrast to the base of the Flathead aquifer, upper surfaces of component formations generally are conformable with or gradational into overlying Paleozoic formations, although unconformities are present locally. For example, the Flathead Sandstone is conformably overlain by the Gros Ventre Formation at the northwestern end of the Wind River Mountains and grades into the Gros Ventre Formation and Gallatin Limestone at the southeastern end of this range, but the Flathead Sandstone has been truncated by pre-Mississippian erosion southeast of the Rawlins Uplift (fig. 12). Similarly, the upper part of the Lodore Formation in the Uinta Mountains grades northward into rocks equivalent to the Gros Ventre Formation and westward into the Ophir Shale. However, the Lodore Formation is overlain unconformably by Mississippian rocks at the southeastern end of the Uinta Mountains (Kinney, 1955, p. 23–24) and has been eroded completely from the north flank of this range and from small areas on the south flank of the range (Huddle and others, 1951; Hansen, 1965b, p. 38). At the northeastern end of the Sawatch Range, the contact between the Sawatch Quartzite and Peerless Formation generally is

FIGURE 11.—Cambrian Ignacio Quartzite at Coalbank Pass in the San Juan Mountains, Colo.

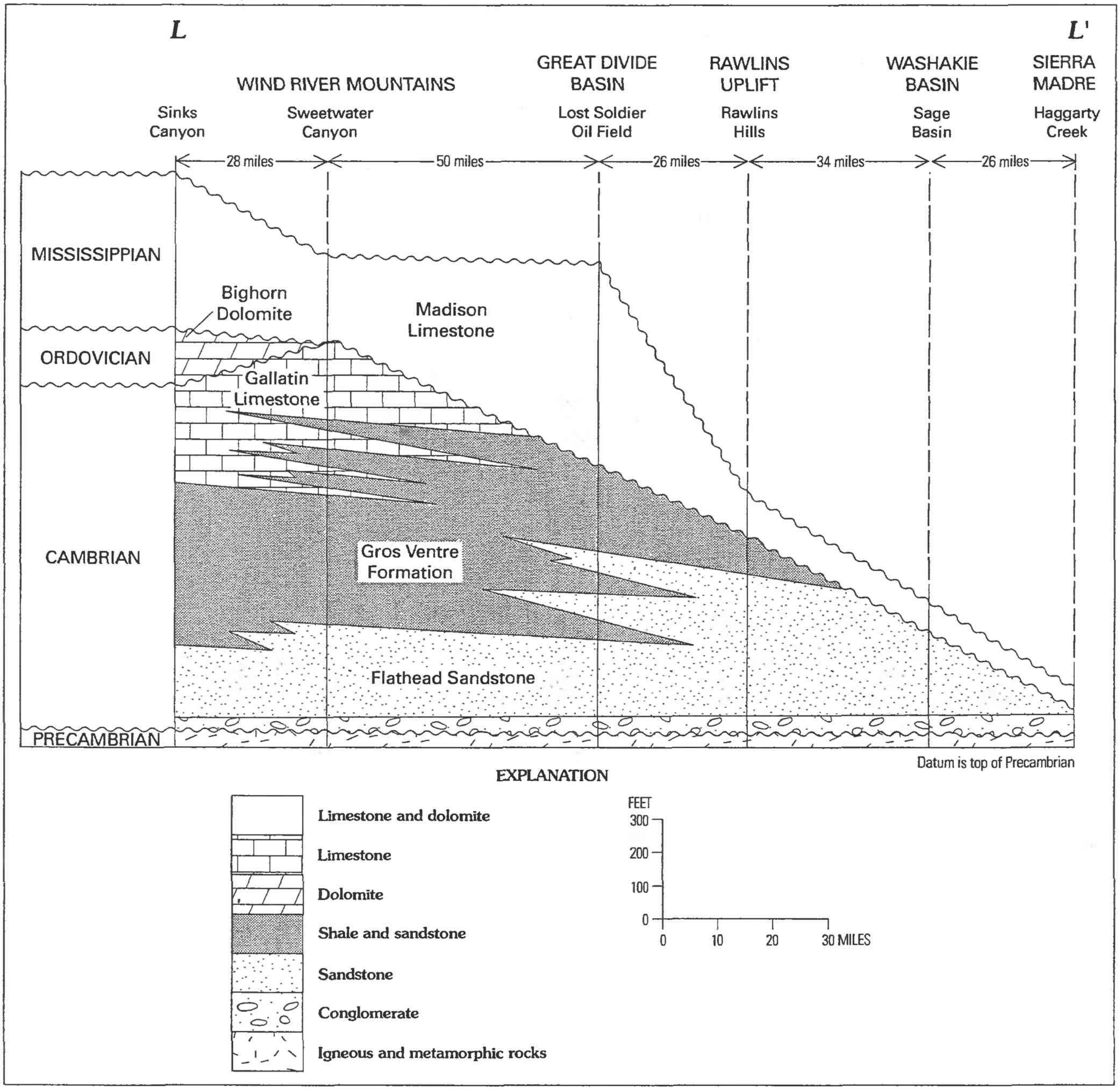



FIGURE 12.—Stratigraphic section showing relations among lower and middle Paleozoic rocks, Wind River Mountains to Sierra Madre, Wyo. Compiled from Barlow (1951), Ritzma (1951), Berry (1960), and Keefer and Van Lieu (1966); location of section shown on plate 6.

gradational, but in the Gore Range, both units have been truncated by pre-Pennsylvanian erosion (Donner, 1949, p. 1221; Singewald, 1951, p. 11). The Sawatch Quartzite is overlain unconformably by the Manitou Dolomite in the southern Sawatch Range (Dings and Robinson, 1957, p. 11). The Ignacio Quartzite grades westward into the Bright Angel Shale (fig. 13), but locally it has been truncated or removed by pre-Devonian erosion (Loleit, 1963, p. 27–29: Baars and others, 1987, p. 345). Contacts between the Tapeats Sandstone and equivalent strata and the Bright Angel Shale and equivalent strata from the Grand Canyon to the San Juan River are transitional (Irwin and others, 1971, p. 5–6). The Tintic Quartzite conformably is overlain by the Ophir Shale (Cooper, 1960, p. 69).

## GROS VENTRE CONFINING UNIT

Shaly sediments deposited seaward of Cambrian shorelines and on top of beach and littoral sands as the sea transgressed make up the Gros Ventre confining unit (pl. 8). Component geologic units include the Gros Ventre Formation, the upper

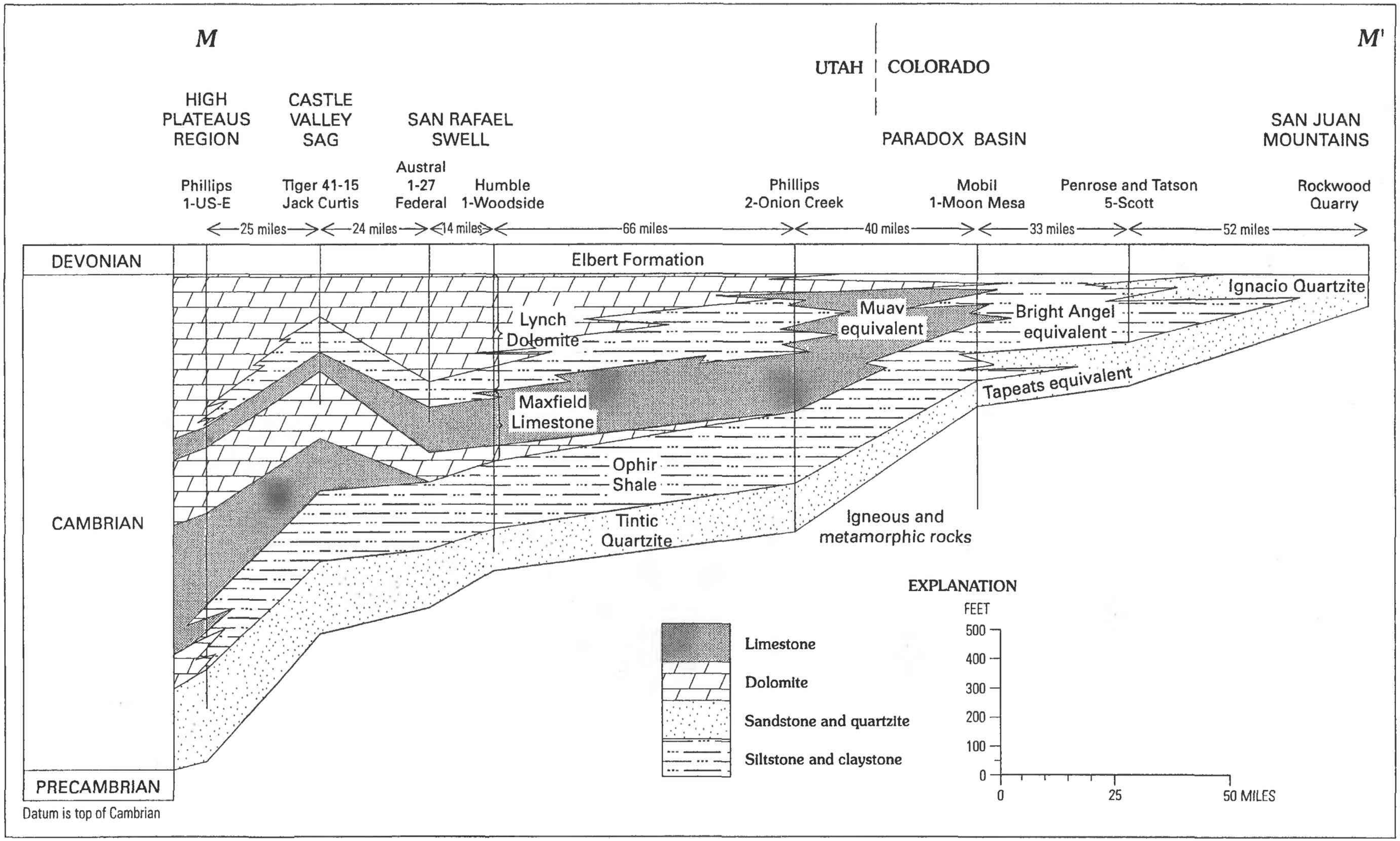



FIGURE 13.—Stratigraphic section showing relations among Cambrian formations in southwestern Colorado and southeastern Utah. Compiled from Baars and Knight (1957) and unpublished logs prepared by American Stratigraphic Co. Thickness of basal sandstone unit extrapolated from plate 6 where wells do not fully penetrate the formations; location of section shown on plate 6.

(predominantly shaly) part of the Lodore Formation, the Bright Angel Shale, the Ophir Shale (Formation), and unnamed equivalents (table 1 and pl. 5). These geologic units decrease in age from Early and Middle Cambrian on the western side of the area to Late Cambrian on the eastern side (Huddle and others, 1951; Untermann and Untermann, 1954, p. 25; Baker and Crittenden, 1961; Middleton and others, 1980; Baars, 1983, p. 51; Love and others, 1993).

Becoming thicker toward depositional centers in the greater Green River, Paradox, and Kaiparowits Basins in the UCRB and the Wasatch Range west of the UCRB, the Gros Ventre confining unit reaches a maximum thickness of about 1,100 ft in the UCRB (pl. 8). Because of erosion or nondeposition, the confining unit is not present in the central third of the study area.

## COMPONENT GEOLOGIC UNITS

In Wyoming, the Gros Ventre confining unit consists of the Gros Ventre Formation (fig. 14). In the northwestern corner of the study area, the Gros Ventre Formation is separable into three members, which in ascending order are the Wolsey Shale, Death Canyon Limestone, and Park Shale Members (Middleton and others, 1980). The Wolsey Shale Member in the Snake River Range of the Overthrust Belt consists of interbedded olive-gray to light-gray, fissile, micaceous shale and flat-pebble-limestone conglomerate (Wanless and others, 1955, p. 12). Eastward, the Wolsey Shale Member contains less limestone and more sandstone, and in the Gros Ventre Range and northwestern Wind River Mountains, it consists of interbedded greenish-gray, tan, and pink micaceous, sandy shale and glauconitic, hematitic, and quartzitic sandstone (Foster, 1947, p. 1540–1548; Keefer and Van Lieu, 1966, p. 15–16). The Death Canyon Limestone Member in the Overthrust Belt and Gros Ventre Range consists of thinly to massively bedded, gray to bluish-gray, tan, and brown, crystalline limestone and dolomitic limestone with interbeds of oolitic limestone, limestone breccia and conglomerate, and green shale (Wanless and others, 1955, p. 13; Oriel, 1969, p. 6; Simons and others, 1988, p. 8). Eastward, in the northwestern Wind River Mountains, the Death Canyon Limestone Member consists of thinly bedded, gray, crystalline limestone underlain by limestone and shale (Keefer and Van Lieu, 1966, p. 16). The Park Shale Member in the Overthrust Belt, Gros Ventre Range, and northwestern Wind River Mountains consists of fissile, grayish-green, micaceous, glauconitic shale with scattered interbeds of shaly sandstone, platy limestone, and flat-pebble-limestone conglomerate (Wanless and others, 1955, p. 13; Keefer and Van Lieu, 1966, p. 16; Oriel, 1969, p. 6).

As the Gros Ventre Formation grades laterally into the Flathead Sandstone, Sawatch Quartzite, and Lodore Formation eastward and southward from the Wind River Mountains, the number of sandstone layers increases, the number of carbonate and shale layers decreases, and the Gros Ventre Formation loses its tripartite identity. At the southeastern end of the Wind River Mountains, the Gros Ventre Formation consists of interbedded shale and sandstone with numerous thin layers of limestone and flat-pebble-limestone conglomerate in the upper half of the formation (Keefer and Van Lieu, 1966, p. 17). In the Rawlins area, the Gros Ventre Formation (locally called the Buck Springs Formation) consists of interbedded red and grayish-green sandy shale, siltstone, and glauconitic, micaceous sandstone (uppermost Cambrian rocks described by Berry, 1960, p. 70–71).

FIGURE 14.—Cambrian Gros Ventre Formation in the channel of Clear Creek, a tributary of the Green River near the northwestern end of the Wind River Mountains, Wyo.

In the southeastern Uinta Mountains, the upper (shaly) part of the Lodore Formation is very similar in lithology to the Gros Ventre Formation of the Rawlins area. In Dinosaur National Monument, the upper part of the Lodore Formation (fig. 4) consists of pink, tan, and greenish-gray, glauconitic shale that is interbedded with tan to pale-green glauconitic sandstone and overlain by ledge-forming, light-brown to greenish-gray sandstone (Hansen and others, 1983).

The equivalent of the Gros Ventre Formation from the southwestern Uinta Mountains to the vicinity of Lake Powell in southeastern Utah is the Ophir Shale. Outcrops are rare in the Uinta Mountains because of pre-Mississippian erosion, but a 110-ft-thick sequence of interbedded shale and glauconitic sandstone described by Huddle and others (1951) in the Moon Lake area between rocks that they called Pine Valley Quartzite and Upper Cambrian(?) limestone (interpreted in this report to be the Tintic Quartzite and Maxfield Limestone), probably is the Ophir Shale. In the Wasatch Range west of the Uinta Basin (14–26 mi west of the divide separating streams draining into the UCRB from those draining into the Basin and Range province), outcrops of the Ophir Shale (locally called Ophir Formation) consist of olive-green, micaceous shale overlain, in turn, by gray limestone and dolomite, and olive-green to brown sandstone and shale (Baker and Crittenden, 1961; Baker, 1964). Consistent with outcrops in the Wasatch Range, the Ophir Shale in boreholes within the UCRB consists of grayish-green and red shale and sandy shale with numerous interbeds of beige and red, commonly glauconitic limestone and sandstone (Cooper, 1960, p. 69–73).

Considering lateral facies variations, there is no lithological basis for distinguishing the Bright Angel Shale from the Ophir Shale, and the names are applied loosely among geologists working in southeastern Utah and southwestern Colorado (Baars, 1958, p. 97). The distinction between the Bright Angel Shale and unnamed equivalent strata in southeastern Utah and southwestern Colorado and the Ophir Shale in this report arbitrarily is made along an axis of thinning that extends in a curve from the Uncompahgre Plateau of southwestern Colorado to the Fish Lake Plateau of southeastern Utah. Where the Bright Angel Shale crops out in the Grand Canyon (fig. 2), the formation consists of thinly bedded, green and tan, micaceous shale and sandstone with scattered layers of brown limestone and dolomite and green and reddish-purple crossbedded, glauconitic sandstone (Noble, 1922, p. 39–42).

### UPPER CONTACTS

Contacts between formations comprising the Gros Ventre confining unit and overlying Cambrian and Mississippian formations vary from gradational to unconformable. From the Overthrust Belt to the eastern Wind River Mountains, the Gros Ventre Formation is overlain unconformably by the Gallatin Limestone of Cambrian age (Foster, 1947, p. 1547; Keefer and Van Lieu, 1966, p. 18). At the eastern end of the Wind River Mountains, however, the Gros Ventre Formation grades into the Gallatin Limestone (fig. 12). East and south of the Wind River Mountains, the Gros Ventre Formation has been truncated by pre-Mississippian erosion and is overlain unconformably by the Madison Limestone of Mississippian age. This unconformity at the southeastern end of the Uinta Mountains is indicated only by a westward thinning of the Lodore Formation (Kinney, 1955, p. 22–23). The contact between the Ophir Shale (Formation) and Maxfield Limestone is gradational where it can be observed in the Wasatch Range (Baker and Crittenden, 1961; Baker, 1964). Locally, in the Wasatch Range and Uinta Mountains, the Maxfield Limestone has been removed by erosion, and the Ophir Shale is overlain unconformably by Mississippian rocks. In the subsurface of southeastern Utah, the Ophir Shale is overlain conformably by the Maxfield Limestone (Cooper, 1960). In the Grand Canyon and areas to east, the Bright Angel Shale and equivalent strata grade upward and laterally into the Muav Limestone and equivalent strata (fig. 13).

## BIGHORN AQUIFER

The Bighorn aquifer (pl. 9) consists of carbonate rocks deposited at the peak of the first Paleozoic marine transgression and the erosional remnants of a second Paleozoic marine incursion (Foster, 1972; Kent, 1972; Lochman-Balk, 1972). Component geologic units deposited during the initial transgression include the Gallatin Limestone, Dotsero Formation, Peerless Formation, Muav Limestone and equivalents, Maxfield Limestone, Lynch Dolomite, and Manitou Dolomite (table 1 and pl. 5). On the basis of faunal evidence, these formations are considered to be mostly Middle to Upper Cambrian (Bass and Northrop, 1963, p. 10; Baker, 1972; Middleton and others, 1980; Baars, 1983, p. 51), but the Lynch Dolomite could be Upper Cambrian and Lower Ordovician (Clark, 1963, p. 62–63), and the Manitou Dolomite is Lower Ordovician (Bass and Northrop, 1963, p. 16–17). The spatial distribution of these formations indicates either progressive onlap or pre-Mississippian erosion from west to east across the area.

Component geologic units deposited during the second marine incursion include the Harding Sandstone, Fremont Limestone, and Bighorn Dolomite (table 1). The Harding Sandstone and the Lander Sandstone Member of the Bighorn Dolomite, which represent the beach and littoral deposits of the second marine advance, are preserved in isolated areas at the southeastern end of the Wind River Mountains in Wyoming and in the Sawatch Range and Elk Mountains in Colorado (Foster, 1972, p. 85; Ross and Tweto, 1980). The Fremont Limestone is preserved only at the southern end of the Sawatch Range and in the Elk Mountains (Ross and Tweto, 1980). The main body of the Bighorn Dolomite is preserved north and west of the Rock Springs Uplift in Wyoming (Foster, 1972). On the basis of faunal evidence, the erosional remnants of the second marine advance generally are considered to be Middle and Upper Ordovician (Dings and Robinson, 1957, p. 13; Keefer and Van Lieu, 1966, p. 23–25). However, the existence of Silurian carbonate xenoliths in diatremes on the Colorado-Wyoming border (Ross and Tweto, 1980, p. 52–53) and the prevailing carbonate lithology of Silurian deposits near the study area (Kent, 1972, p. 57) indicate that the second marine advance persisted until the Silurian in the area of the UCRB. The uppermost part of the Bighorn Dolomite, the Leigh Dolomite Member contains a fauna that could be interpreted as Early Silurian (Wanless and others, 1955, p. 15–16).

The Bighorn aquifer generally thickens from east to west across the study area, but a slight reversal of this trend occurs in the Sawatch Range and vicinity because of the presence of remnant Ordovician rocks. Thicknesses on the western side of the area range from 1,200 to 3,000 ft; the maximum thickness on the eastern side is about 400 ft. Whether thinned by erosion or nondeposition, the geologic units that comprise the Bighorn aquifer are missing in the central part of the UCRB and along most of its eastern edge. The aquifer is at or near land surface on the flanks of uplifted areas, but it typically is 5,000–34,000 ft deep in structural basins. The top of the Bighorn aquifer is less than 1,500 ft above the Flathead aquifer in most areas (see pl. 7 for depths to the top of the Flathead aquifer). However, the Bighorn aquifer is as much as 2,500 ft above the Flathead aquifer in the Green River Basin and in the Overthrust Belt of southwestern Wyoming and is as much as 4,000 ft above the lower aquifer in the Henry Mountains Basin and High Plateaus region of southeastern Utah.

### COMPONENT GEOLOGIC UNITS OF CAMBRIAN AGE

Cambrian rocks included in the Bighorn aquifer in southwestern Wyoming are assigned to the Gallatin Limestone, which also is known as the Boysen Formation (Foster, 1947). In the Gros Ventre Range and Overthrust Belt, the Gallatin Limestone consists of thin- to medium-bedded, gray, bluish-gray, and brown-mottled, finely to coarsely crystalline limestone and dolomitic limestone with interbeds of sandy, oolitic, and bioclastic limestone, limestone conglomerate, and green shale (Foster, 1947, p. 1540–1548; Wanless and others, 1955, p. 14; Oriel, 1969, p. 7; Rubey and others, 1975, p. 3). At the northwestern end of the Wind River Mountains, the Gallatin Limestone is divisible into three members (Middleton and others, 1980), which in ascending order include the Du Noir Limestone Member, Dry Creek Shale Member (of Shaw, 1957), and Open Door Limestone Member. The Du Noir Limestone Member consists of thinly bedded, gray, very glauconitic and oolitic limestone with some layers of flat-pebble conglomerate. The Dry Creek Shale Member consists of greenish-gray shale with minor interbeds of gray limestone. The Open Door Limestone Member, which comprises most of the formation, consists of thinly to massively bedded, gray limestone with a few layers of flat-pebble conglomerate and irregular patches of granular limestone. Southeast of the Wind River Mountains, at Crooks Gap, the Gallatin Limestone has been reduced by pre-Mississippian erosion to a thin interval of purple, sandy limestone (Thomas, 1951, p. 32). Nineteen miles southeast of this outcrop, in the Lost Soldier oil field, the Gallatin Limestone is missing (Barlow, 1951).

Equivalents of the Gallatin Limestone in northwestern Colorado include the laterally gradational Dotsero Formation (fig. 15) and Peerless Formation. Both of these formations are characterized by major changes in lithology within short distances. At the southern end of the Axial Basin Arch, for example, the Dotsero Formation varies from predominantly pink and brown glauconitic dolomite to varicolored glauconitic and quartzitic sandstone, shale, and oolitic dolomite within a horizontal distance of about 18 mi (American Stratigraphic Co., unpublished drilling logs). At the southeastern end of the White River Plateau, the Dotsero Formation consists of thinly bedded, tan and gray, glauconitic dolomite and flat-pebble-limestone conglomerate with interbeds of greenish-gray shale and a capping layer of algal limestone

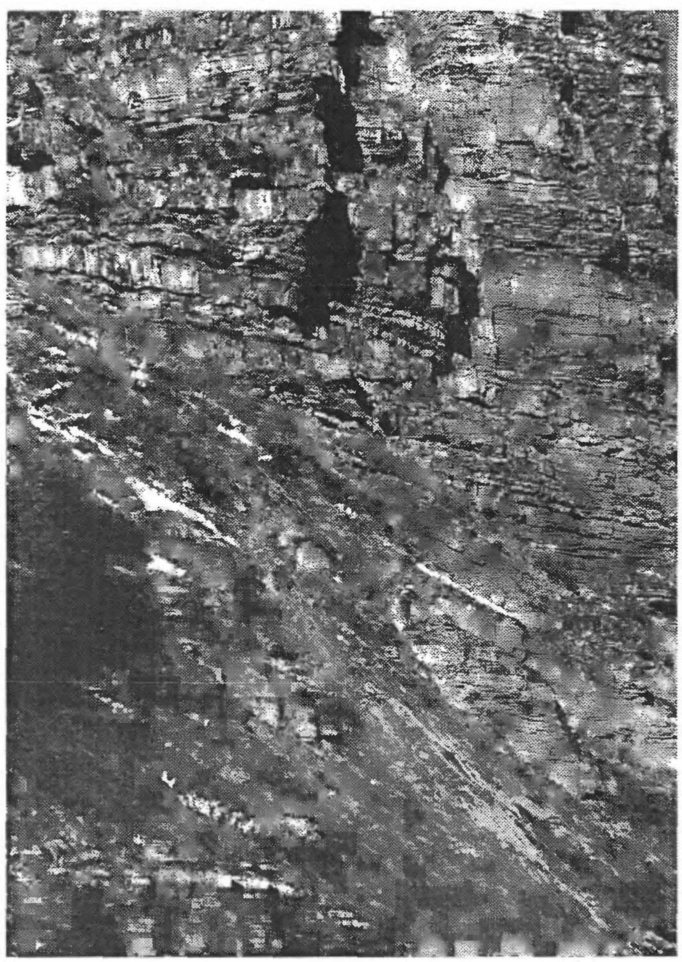


FIGURE 15.—Cambrian Dotsero Formation overlain by Ordovician Manitou Dolomite in Glenwood Canyon, Colo.

(Bass and Northrop, 1963, p. 10). Toward the Sawatch Range, the algal limestone bed pinches out, and the Dotsero Formation grades into the Peerless Formation (Gerhard, 1972, p. 6). On the west side of the Sawatch Range, the Peerless Formation consists of grayish-orange dolomitic sandstone and sandy dolomite and red, ochre, and gray shale, with a few beds of flat-pebble conglomerate (Bryant, 1979, p. 14–15). On the east side of the Sawatch Range, the Peerless Formation can be nearly all sandstone, shale, or dolomite but commonly consists of tan, maroon, and green sandy dolomite, flat-pebble conglomerate, dolomitic sandstone, and shale (Tweto, 1949, p. 161–165; Tweto and Lovering, 1977, p. 19). On the east side of the Gore Range, the Peerless Formation in ascending order consists of thinly to massively bedded, purple and black pebbly quartzite; brown-weathering dolomite; thinly bedded, green shale with interbedded dolomite; and thinly bedded, olive-green and brown dolomite with interbedded green shale (Singewald, 1951, p. 9).

Outcrops in the Wasatch Range described by Baker and Crittenden (1961) and Baker (1972, 1973) indicate that the Gallatin Limestone extends continuously into southeastern Utah west of an area of pre-Mississippian erosion. In the Wasatch Range, however, strata equivalent to the Gallatin Limestone are assigned to the Maxfield Limestone. The thickness of the Maxfield Limestone varies substantially within short distances because of the pre-Mississippian erosion, and locally the formation has been removed entirely. Fairly complete sections consist of thinly to massively bedded, gray, yellow, and brown, mottled limestone with oolitic or pisolitic beds near the base overlain by massively bedded, medium-gray to nearly white dolomite. On the southwestern side of the Uinta Mountains, light-gray and brown limestone mapped by Huddle and others (1951) as Upper Cambrian(?) limestone is interpreted in this report to be an erosional remnant of the Maxfield Limestone. In southeastern Utah, northwest of an axis of thinning that extends from the vicinity of Lake Powell to the Uncompahgre Plateau, the Maxfield Limestone (locally called Bowman-Hartman Limestone) in boreholes consists of massively bedded, gray and tan, commonly glauconitic, fine-grained, sucrose, oolitic or stromatolitic limestone with thin to thick intervals of white, tan, and brown dolomite and thin interbeds of green, gray, and black shale (Cooper, 1960, p. 73).

Overlying the Maxfield Limestone in boreholes in southeastern Utah, predominantly dolomitic strata, probably equivalent to the upper dolomite interval of the Maxfield Limestone in the Wasatch Range, generally have been assigned to the Lynch Dolomite (Hintze, 1973). The Lynch Dolomite in southeastern Utah (Cooper, 1960, p. 73) predominantly consists of massively bedded, gray, brown, and beige, fine-grained, crystalline, sucrose, oolitic, stromatolitic, and cherty dolomite with intervals of grayish-green, micaceous shale, sandstone, and limestone. The nondolomitic beds are most abundant toward the base and eastern margin, where the Lynch Dolomite grades into the Maxfield Limestone and Ophir Shale.

South and east of the limits of Maxfield-Lynch terminology, equivalent strata are assigned to the Muav Limestone or are unnamed. The Muav Limestone crops out in canyons of the Colorado and Little Colorado Rivers south of Lees Ferry, Ariz. McKee and Resser (1945) divided the Muav Limestone in the Grand Canyon (fig. 2) into seven members overlain by dolomite. The five lowest members pinch out eastward and become carbonate tongues in the Bright Angel Shale. Noble (1922) considered the Muav Limestone in the Grand Canyon to be divisible into four informal stratigraphic units, which in ascending order consist of (1) thinly bedded, gray and buff, mottled, oolitic limestone interlayered with intraformational conglomerate; (2) thinly bedded, mottled limestone, intraformational conglomerate, micaceous to calcareous sandstone, and shale; (3) crystalline limestone and dolomite with intraformational conglomerate; and (4) massively bedded, vuggy dolomite. Eastward, in Arizona, Utah, and Colorado, unnamed beds equivalent to the Muav Limestone become increasingly shaly, as they grade into beds equivalent to the Bright Angel Shale (fig. 13).

As designated in this report, the Lynch Dolomite and beds equivalent to the Muav Limestone incorporate most of the rocks assigned to the Aneth Formation by Knight and Cooper (1955) in the Four Corners area. The Aneth Formation consists of brown, gray, and green, shaly, glauconitic, and oolitic dolomite with black shale interbeds that are particularly abundant in the upper part of the formation. On the basis of fish plates found in the Shell 1-Bluff well (SLD 39-23-32abb), Knight and Cooper (1955) assigned the Aneth Formation to the Devonian System. However, Clark (1963, p. 62–63) indicated that the Aneth Formation in other wells also contains Cambrian and Ordovician trilobite, brachiopod, and conodont fossils. The age of the Aneth Formation, therefore, is questionable. For the Aneth Formation to exist as a separate, lithologically and paleontologically distinct formation requires an abrupt scouring of lithologically similar Cambrian carbonate rocks. (See, for example, Parker and Roberts, 1963, p. 42.) Such profound erosion is unlikely to have occurred in the relatively stable tectonic setting of the Four Corners area. More likely, as suggested by Clark (1963, p. 64), most of the so-called Aneth Formation is a lateral facies equivalent of the Lynch Dolomite and Muav Limestone. Assuming that the fish plates in the Shell 1-Bluff well were identified correctly, some or all of the beds designated as Aneth Formation in this well probably represent a basal facies of the Devonian Elbert Formation that may not extend far beyond the vicinity of the well.

## COMPONENT GEOLOGIC UNITS OF ORDOVICIAN AGE

In southwestern Wyoming, the entire Ordovician sequence is assigned to the Bighorn Dolomite (fig. 16). In this area, the Bighorn Dolomite is divisible into three members: the Lander Sandstone Member, the unnamed middle member (most of the formation), and the Leigh Dolomite Member. The Lander

FIGURE 16.—Ordovician Bighorn Dolomite (cliff-forming unit) in the Salt River Range of the Overthrust Belt in Wyoming. The thickness, here, has been doubled by imbricate thrust faults.

Sandstone Member occurs in lenticular bodies less than 5 ft thick at the southeastern end of the Wind River Mountains (Keefer and Van Lieu, 1966, p. 22). It is a tan and gray, fine- to coarse-grained sandstone that contains fragments of Cambrian carbonate rocks. The unnamed middle member of the Bighorn Dolomite, as described by Foster (1947, p. 1548–1549) in the Gros Ventre Range, by Oriel (1969, p. 7) in the Overthrust Belt, and by Keefer and Van Lieu (1966, p. 22) in the Wind River Mountains, is a massively bedded, beige and light-gray mottled, granular dolomite that is about 300–1,000 ft thick. The Leigh Dolomite Member, varying from 0 to 85 ft thick, consists of very thin bedded (flaggy), white, light-gray, and pink, fine-grained dolomite (Foster, 1947, p. 1549; Keefer and Van Lieu, 1966, p. 22).

In northwestern Colorado, the Ordovician sequence in ascending order consists of the Manitou Dolomite, the Harding Sandstone, and the Fremont Limestone. The Harding Sandstone is the lateral equivalent of the Lander Sandstone Member of the Bighorn Dolomite; the Fremont Limestone is the lateral equivalent of the unnamed middle member of the Bighorn Dolomite. The Manitou Dolomite generally is the only Ordovician formation present. However, erosional remnants of the Harding Sandstone and Fremont Limestone occur in the southern Elk Mountains, and the Harding Sandstone constitutes the entire Ordovician sequence between the Sawatch and Gore Ranges.

The Manitou Dolomite predominantly consists of dolomite but varies in texture and bedding characteristics from area to area. In Glenwood Canyon on the southeastern side of the White River Plateau, the formation (fig. 15) is divisible into a lower member consisting of gray, thin-bedded, limestone-pebble conglomerate, brown limestone and dolomite, and greenish-gray, limy shale, and an upper member consisting of brown, thin-bedded, siliceous dolomite (Bass and Northrop, 1963, p. 14). In the southern Sawatch Range and Elk Mountains, the Manitou Dolomite consists of predominantly gray, thin- to medium-bedded, fine-grained to crystalline dolomite with stringers and nodules of chert and interbeds of pink shale (Dings and Robinson, 1957, p. 11; Mallory, 1957; Gerhard, 1972, p. 8; Bryant, 1979, p. 15). In the Gore Range, the Manitou Dolomite consists of white and bluish-gray crystalline dolomite with siliceous layers (Singewald, 1951, p. 9).

The Harding Sandstone is less than 10 ft thick in most places where it is present. Variations in texture are best observed in two places where the Harding Sandstone is about 40 feet thick. In the Minturn area, at the northeastern end of the Sawatch Range, the Harding Sandstone consists of lenticular masses of white quartzite overlain by thin-bedded green and maroon sandstone, quartzite, and conglomerate with shale interbeds (Tweto and Lovering, 1977, p. 21–22). In the Garfield area, at the southern end of the Sawatch Range, the Harding Sandstone characteristically consists of white, bluish-gray, and black quartzite (Dings and Robinson, 1957, p. 12).

The Fremont Limestone is present only in the southern Elk Mountains and Sawatch Range. In the Crested Butte area, at the southern end of the Elk Mountains, the Fremont Limestone consists of massively bedded, gray and brown, fine-grained dolomite (Mallory, 1957). In the Garfield area, at the southern end of the Sawatch Range, the Fremont Limestone consists of massively bedded, bluish-gray crystalline dolomite (Dings and Robinson, 1957, p. 13).

#### CONTACTS

Contacts between Cambrian and Ordovician formations, between Ordovician formations, and between Ordovician and younger formations generally are unconformable. In southwestern Wyoming, for example, the Bighorn Dolomite unconformably overlies the Gallatin Limestone and underlies the Devonian Darby Formation from the Snake River Range to the southern Wind River Mountains. The pre-Ordovician erosional surface has relief ranging from 100 ft in the northwestern Wind River Mountains to 3 ft in the southeastern part of this range (Keefer and Van Lieu, 1966, p. 20), and, locally, the Lander Sandstone Member of the Bighorn Dolomite fills channels cut into this surface. The pre-Devonian erosional surface has a relief of as much as 20 ft; breccia and sandstone deposits at the base of the Devonian Darby Formation fill channels cut into this surface (Keefer and Van Lieu, 1966, p. 23–28). From the southern end of the Wind River Mountains to the area west of Rawlins, pre-Mississippian erosion has removed rocks from Devonian to Cambrian age; in this area, the Mississippian Madison Limestone from west to east successively truncates the Darby Formation, Bighorn Dolomite, and Gallatin Limestone (fig. 12).

In northwestern Colorado, contacts between the Dotsero and Peerless Formations of Cambrian age and the Manitou Dolomite of Ordovician age generally are gradational (Gerhard, 1972, p. 10–11). However, because the Ordovician formations are erosional remnants, the Manitou Dolomite does not overlie the Dotsero and Peerless Formations wherever they occur. Where the Manitou Dolomite is missing, the Ordovician Harding Sandstone, Devonian Parting Formation, or Devonian to Mississippian(?) Dyer Dolomite may overlie the Dotsero and Peerless Formations. The Ordovician Manitou Dolomite, Harding Sandstone, and Fremont Limestone are separated from each other and from Devonian rocks by regional unconformities (Tweto and Lovering, 1977, p. 21–22).

In southwestern Colorado, southeastern Utah, and northeastern Arizona, major erosional unconformities separate Cambrian carbonate formations from Devonian and Mississippian rocks. Throughout most of its areal extent, the Maxfield Limestone–Lynch Dolomite sequence is overlain unconformably by the Elbert Formation (Cooper, 1960, p. 73). However, in the Wasatch Range and Uinta Mountains bordering the western Uinta Basin, the Lynch Dolomite and Maxfield Limestone successively have been truncated by pre-Mississippian erosion and are overlain unconformably by Mississippian formations (Huddle and others, 1951; Baker and Crittenden, 1961; Baker, 1973). The Muav Limestone and unnamed equivalent strata to the east are overlain unconformably by the Devonian Temple Butte and Elbert Formations, although where observed in the Grand Canyon, the unconformity generally parallels bedding (Irwin and others, 1971, p. 7).

## ELBERT-PARTING CONFINING UNIT

The Elbert-Parting confining unit (pl. 10) is composed of the lithologically diverse initial deposits of a third Paleozoic marine transgression (Baars, 1972; Kent, 1972). Component geologic units include the Darby, Parting, and Elbert Formations and the Cottonwood Canyon Member of the Madison and Lodgepole Limestones (table 1 and pl. 5). The Temple Butte Formation of the Grand Canyon area grades into the Elbert Formation along an indefinite boundary at or near the southwestern edge of the UCRB. Paleontological data indicate that most of the component formations are Upper Devonian (Bass and Northrop, 1963, p. 20–21; Benson, 1966; Keefer and Van Lieu, 1966, p. 27; Baars and others, 1987, p. 346). However, channel deposits at the base of the Darby Formation in the Wind River Mountains contain Early Devonian fish remains, and the upper part of the Cottonwood Canyon Member contains Early Mississippian conodonts (Sando, 1979, p. 5).

Formations comprising the Elbert-Parting confining unit apparently were deposited in three basins, which are separated by areas where the formations are thin to absent (pl. 10). In Wyoming, the Darby Formation and Cottonwood Canyon Member thicken westward from zero on the Rock Springs Uplift to about 1,100 ft in the Overthrust Belt. The thickness of the Parting Formation in northwestern Colorado and the Uinta Basin increases from zero to more than 150 ft toward the center of its depositional basin. The thickness of the Elbert and Temple Butte Formations in southwestern Colorado, southeastern Utah, and northeastern Arizona increases from zero at the edges of the Uncompahgre Plateau, San Juan Mountains, San Juan Basin, and Grand Canyon area to more than 300 ft in the High Plateaus region and more than 400 ft in the Black Mesa Basin. The Elbert-Parting confining unit is missing in Wyoming east of the Rock Springs Uplift; in the Uinta Mountains and most of the Uinta Basin; in northwestern Colorado north of the Yampa River, south of the Piceance Basin and Elk Mountains, and east of the Sawatch and Gore Ranges; in the Uncompahgre and Gunnison Plateaus; and in parts of the San Juan Mountains and Four Corners Platform. Thickness and lithofacies patterns indicate that geologic units that comprise the Elbert-Parting confining unit were eroded from the centers of the White River Plateau and Sawatch Range but did not extend much beyond present limits in other areas.

#### COMPONENT GEOLOGIC UNITS

Rocks comprising the Elbert-Parting confining unit in Wyoming are assigned mostly to the Darby Formation, which has extremely variable lithology. However, despite the lateral discontinuity of individual layers, the formation as a whole becomes increasingly more clastic eastward across its area of extent.

In the Overthrust Belt and Gros Ventre Range, the Darby Formation (fig. 17) is divisible into three units, which Benson

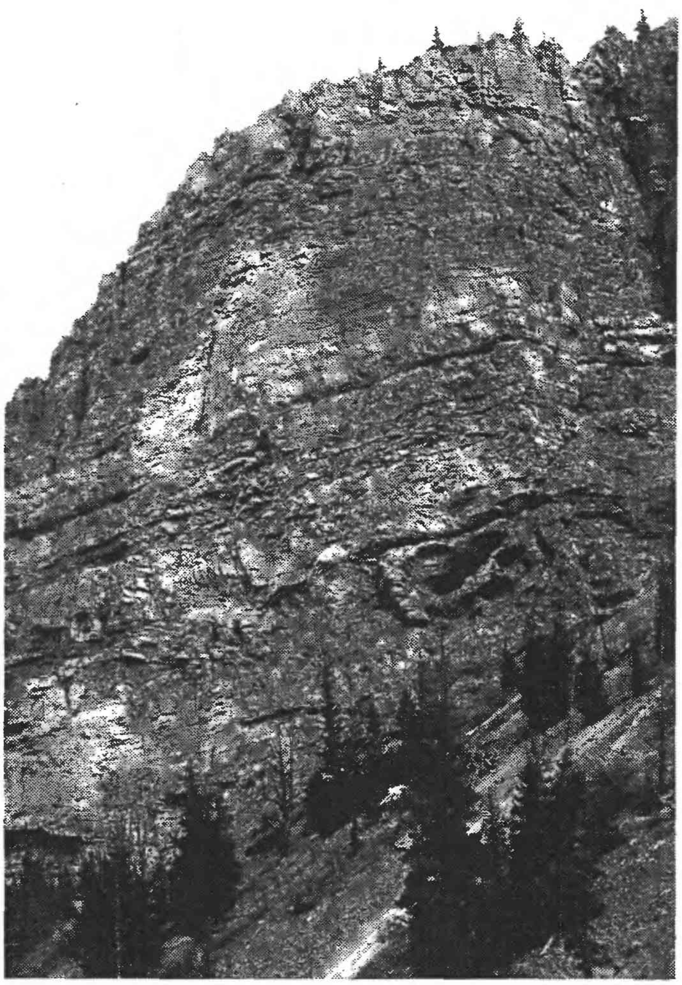


FIGURE 17.—Devonian and Mississippian Darby Formation and Mississippian Lodgepole Limestone on the upthrown side of the Hoback Fault, at the juncture of the Gros Ventre and Hoback Ranges in Hoback Canyon, Wyo.

(1966) considered equivalent to the lower member and Birdbear Member of the Jefferson Formation and the Three Forks Formation. The lowest unit consists of dark-brownish-gray, fine- to medium-crystalline and sucrose, petroliferous dolomite and limestone with interbedded light-gray to white sandstone and siltstone, green and red claystone and mudstone, and, locally, minor solution breccia or anhydrite. The middle unit consists of massively bedded, brownish-gray, finely crystalline dolomite. The upper unit consists of thinly bedded, green, gray, brown, and red, dolomitic shale, shaly dolomite, solution breccia, and anhydrite overlain by gray, shaly to silty, fine-grained dolomite.

To the east, at the northwestern end of the Wind River Mountains, the Darby Formation chiefly consists of varicolored dolomite and limestone overlain by gray and tan cherty dolomite and grayish-green shale (Richmond, 1945). Sandstone layers progressively increase in abundance southward in the Wind River Mountains (Keefer and Van Lieu, 1966, pl. 2) and predominate on the western flank of the Rock Springs Uplift.

Overlying the Darby Formation west of the Rock Springs Uplift is a thin (0–80 ft thick) unit, which is assigned to the Cottonwood Canyon Member of the Lodgepole Limestone in the Overthrust Belt and western Gros Ventre Range and to the Cottonwood Canyon Member of the Madison Limestone elsewhere (Sando, 1979). According to Benson (1966, p. 2599), this unit consists of dark-gray, carbonaceous shale, yellow-brown, silty, crinoidal dolomite and, locally, a basal layer of pebbly sandstone or siltstone.

In northwestern Colorado and the Uinta Basin of Utah, the Parting Formation makes up the Elbert-Parting confining unit. The Parting Formation, like the Darby Formation, exhibits major changes in lithology over short distances (Campbell, 1972, p. 56). In the southern Sawatch Range, for example, the Parting Formation consists mostly of gray dolomite with sandstone and sandy limestone interbeds overlying varicolored shale and limestone (Dings and Robinson, 1957, p. 14). On the northwest side of the Sawatch Range, the Parting Formation consists of tan and white, poorly sorted quartzite with greenish-gray sandstone and shale interbeds and a thin basal layer of green clay-shale (Tweto and Lovering, 1977, p. 24–26). In Glenwood Canyon west of the Sawatch Range, the Parting Formation (fig. 18) consists of interbedded light-green, micaceous shale and sandstone, black shale and dolomite, and tan quartzite (Bass and Northrop, 1963, p. 19–20). In the Wilson Creek oil field, on the Axial Basin Arch, the Parting Formation consists of dolomite with interbeds of red and green shale (Ross, 1986, p. 99). Extreme lithologic variability from outcrop to outcrop is characteristic of the Parting Formation, but regionally, clastic layers decrease and carbonate layers increase from the edges to the center of the depositional basin.

In southwestern Colorado, southeastern Utah, and northeastern Arizona, the Elbert Formation comprises the Elbert-Parting confining unit. The Elbert Formation, like other components of this hydrogeologic unit, is lithologically diverse. On the flanks of the San Juan Mountains, the Elbert Formation (fig. 3) predominantly consists of green, red, and purple shale with interbedded limestone, dolomite, and quartzite (Baars and Knight, 1957, p. 118; Baars and others, 1987, p. 346). At the southwestern edge of the study area, the Elbert Formation consists almost entirely of dolomite and limestone. Throughout most of the region, though, the Elbert Formation contains a basal sandstone interval, a middle carbonate interval, and an upper shale interval.

The basal sandstone interval extends discontinuously from the Defiance Plateau to the Uncompahgre Plateau and from the San Juan Mountains to the area west of the Colorado and Green Rivers (fig. 19). It ranges from less than 5 to about 125 ft thick and consists predominantly of white, light-gray, and red, poorly sorted, commonly glauconitic sandstone and quartzite with minor interbeds of shale, limestone, and dolomite. This interval commonly is called the McCracken Sandstone Member of

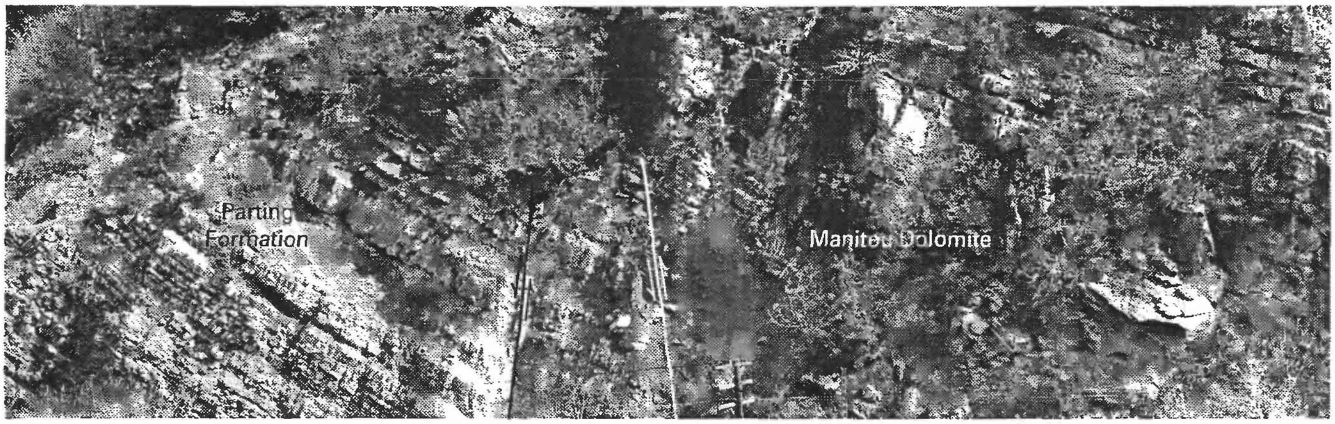



FIGURE 18.—Devonian Parting Formation in fault contact with Ordovician Manitou Dolomite in Glenwood Canyon at Glenwood Springs, Colo.

the Elbert Formation (Knight and Cooper, 1955). However, this name often has been applied inappropriately to the first thick sequence of sandstone or quartzite penetrated by drilling and can include considerable thicknesses of underlying carbonate rocks and shale (see, for example, Parker and Roberts, 1963, p. 40).

The middle carbonate interval comprises most of the Elbert Formation. As described by Cooper (1960, p. 76), this interval consists of thin-bedded, very fine grained to sucrose, locally anhydritic dolomite with thin interbeds of grayish-green, waxy shale, red, clayey shale, and sandstone. The sandstone beds increase in abundance downward in the interval.

From the San Juan Mountains to nearly the western edge of the UCRB, the Elbert Formation is capped by a shale interval (fig. 19) that ranges from less than 5 to 30 ft thick. The shale most typically is waxy green. However, the green layers locally are interbedded with purple or red layers. The shale locally contains discontinuous interbeds of dolomite. Where the shale interval is absent, the contact between the Elbert Formation and the overlying Ouray Limestone is difficult to distinguish.

#### CONTACTS

A major regional unconformity separates formations in the Elbert-Parting confining unit from underlying formations. The Darby, Parting, Elbert, and Temple Butte Formations rest on formations ranging in age from Precambrian to Ordovician.

Geologic units comprising the Elbert-Parting confining unit are overlain conformably in most areas by Devonian and Mississippian rocks. In northwestern Colorado, the Parting Formation is overlain conformably to transitionally by the Upper Devonian to Mississippian(?) Dyer Dolomite (Tweto and Lovering, 1977, p. 27). Similarly, the Elbert Formation in southwestern Colorado, southeastern Utah, and northeastern Arizona is overlain conformably to gradationally by the Upper Devonian Ouray Limestone (Baars and others, 1987, p. 346). However, the Temple Butte Limestone in the Grand Canyon is overlain unconformably by the Mississippian Redwall Limestone (Beus and Lucchita, 1987, p. 7), and the Darby Formation and Cottonwood Canyon Member of the Madison and Lodgepole Limestones in Wyoming are overlain unconformably by other members of the Madison and Lodgepole Limestones (Wanless and others, 1955, p. 19; Keefer and Van Lieu, 1966, pl. 2).

## MADISON AQUIFER

The Madison aquifer of the Northern Great Plains (Downey, 1984) extends into the UCRB, where it is divisible vertically into two zones with different lithologic and hydrologic properties. The lower zone, which consists almost entirely of limestone and dolomite, is named the Redwall-Leadville zone in this report, after the principal component geologic units in Arizona, Colorado, and Utah. The upper zone, which consists of interbedded carbonate rocks, sandstone, shale, solution breccia, and gypsum, is named the Darwin-Humbug zone in this report, after the two geologic units that comprise most of the interval. As shown on plate 7, the Madison aquifer is at or near land surface on the flanks of uplifted areas, but it typically is 5,000 to 32,000 ft deep in structural basins.

### REDWALL-LEADVILLE ZONE

The Redwall-Leadville zone of the Madison aquifer (pl. 11) consists almost entirely of limestone and dolomite deposited during the maximum extent of the third Paleozoic marine transgression (Craig, 1972; Kent, 1972). Component geologic units include the Dyer Dolomite, Ouray Limestone, Gilman Sandstone, Leadville Limestone, and Redwall Limestone; the Mission Canyon Limestone below the lowest evaporite zone of Sando (1977); and the main bodies of the Lodgepole and Madison Limestones (table 1 and pl. 5). All the carbonate formations are so similar in lithology that they probably represent a single depositional history. In an attempt to establish limits for these geologic units on the basis of criteria other than stateline preference, some geologic units were delineated on the basis of

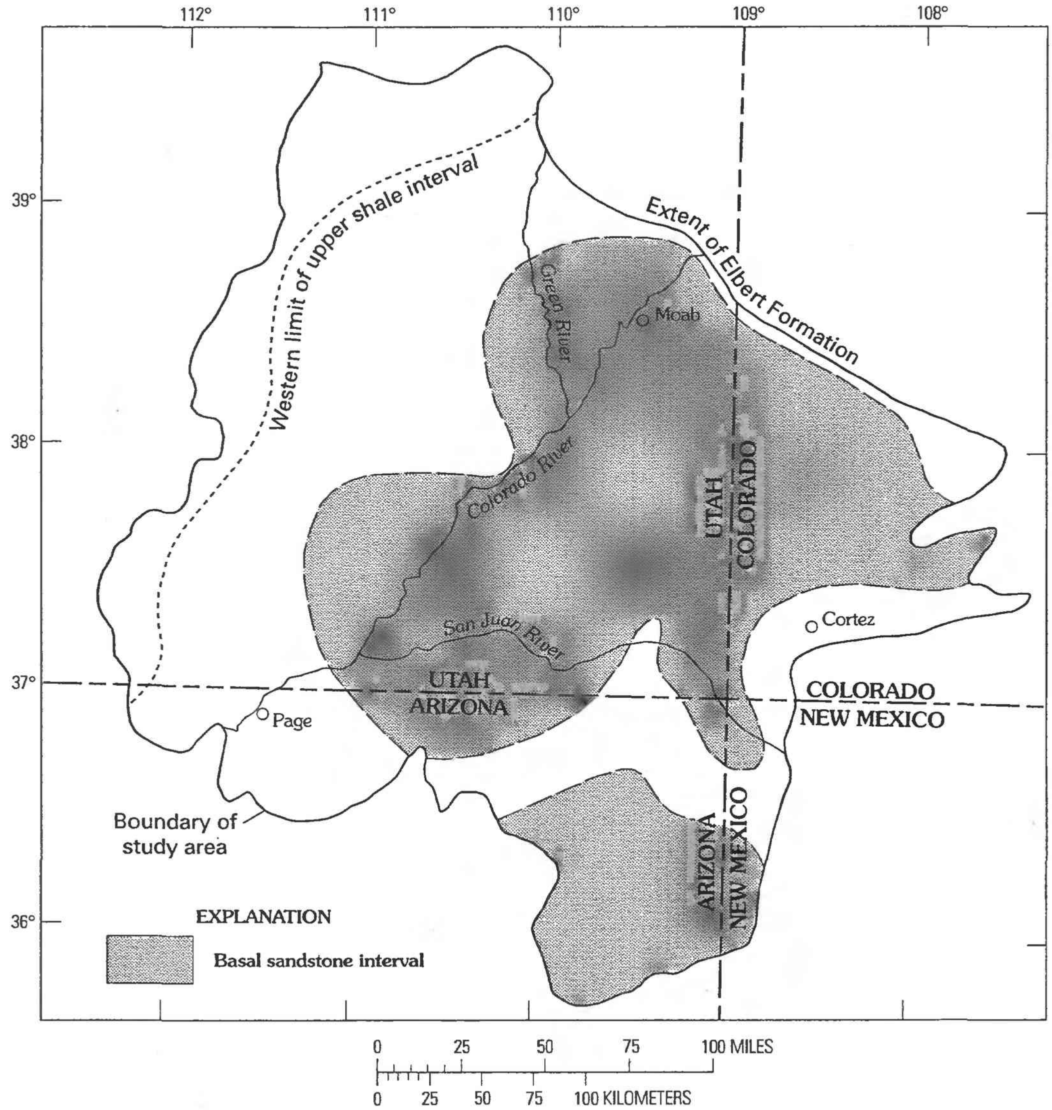



FIGURE 19.—Extent of lithologic subdivisions of the Elbert Formation in the Upper Colorado River Basin. The middle carbonate interval extends to the boundaries of the Elbert Formation. The basal sandstone and upper shale intervals do not extend throughout the area where the Elbert Formation is present; boundaries of these intervals are as shown.

lithologic changes. For example, the boundary between the Leadville and Redwall Limestones along the Colorado-Utah border was established at the change from randomly cherty limestone and dolomite on the east to a four-fold sequence of cherty, oolitic, or anhydritic limestone and dolomite alternating with generally nondescript limestone and dolomite on the west. The eastern facies was assigned to the Leadville Limestone; the western facies to the Redwall Limestone. The boundary between the two formations undulates about the State line, broaching areas previously assigned exclusively to one formation or the other. All other Mississippian geologic units were delimited along axes of thickening or thinning, presumably coincident with changes in the depositional setting. Devonian formations were delimited on the basis of overlying Mississippian formations.

Some established geologic names were not used in this report because no consistent lithological, paleontological, or inferred paleodepositional criteria could be identified for delineating these geologic units. For example, the Madison and Brazer Limestones in the Gros Ventre Range and Wyoming part of the Overthrust Belt, as used by Wanless and others (1955), are not distinguished readily by lithology (Wanless and others, 1955, p. 22). However, in the same area, the names "Lodgepole Limestone" and "Mission Canyon Limestone," as used by Sando (1967, 1977, 1979) are applied consistently. Consequently, the latter names are used in this report.

The Lodgepole and Mission Canyon Limestones also are recognizable in the Utah part of the Overthrust Belt adjacent to the UCRB (in the Wasatch Range) and in the western Uinta Mountains. However, in the Utah part of the Overthrust Belt, the names "Fitchville Formation," "Gardison Limestone," and "Deseret Limestone" are applied in ascending order to strata equivalent to the Lodgepole and Mission Canyon Limestones (see, for example, Baker, 1973). The Lodgepole and Mission Canyon equivalents in the western Uinta Mountains, respectively, have been called either "Madison Limestone" (Huddle and others, 1951) or "Gardison Limestone" (Hintze, 1973) and "Deseret Limestone" (Huddle and others, 1951; Hintze, 1973). Within the Utah Salient of the Overthrust Belt in the UCRB and adjacent areas of the Uinta Basin, either the Wyoming or Utah nomenclature could be applied. In this report, the Fitchville-Gardison-Deseret terminology is not used because it generally has been applied outside the UCRB, and if used in the UCRB, would only pertain to a relatively small area. Exclusive of the Uinta Mountains, the rocks in question simply are called "Lodgepole and Mission Canyon equivalents."

In the Uinta Mountains, the nomenclature of the Mississippian rocks is complicated further because the names "Madison Limestone" and "Deseret Limestone" have been extended throughout the range, even though rocks equivalent to the Mission Canyon Limestone are not present in the eastern part of the range (Hansen, 1965a, p. 39). As a result, different lithologic criteria have been used to distinguish the Madison and Deseret Limestones in different parts of the Uinta Mountains (Huddle and McCann, 1947b; Untermann and Untermann, 1954). To simplify discussion, all Mississippian carbonates below the Humbug Formation in the Uinta Mountains herein are called "Madison Limestone," even though it is recognized that either the Lodgepole–Mission Canyon or Fitchville-Gardison-Deseret terminology could be extended justifiably into the western Uinta Mountains.

Ages of the geologic formations included in the Redwall-Leadville zone are well established by abundant fossil evidence. The Dyer Dolomite and Ouray Limestone are mostly Upper Devonian, but upper layers contain Early Mississippian (Kinderhookian) brachiopods, corals, and foraminifera (Baars and Knight, 1957, p. 121; Bass and Northrop, 1963, p. 22–23; Nadeau, 1972, p. 97–98; Tweto and Lovering, 1977, p. 28; Baars and others, 1987, p. 346). On the basis of stratigraphic position and brachiopods found in equivalent strata in the Wasatch Range, Ferris Mountains, and Washakie Basin (Thomas, 1951; Baker, 1973), the Gilman Sandstone and sandstone at the base of the Madison Limestone probably are Lower Mississippian (Kinderhookian). The Leadville Limestone (Armstrong and Mamet, 1976, p. 20), the main bodies of the Madison and Lodgepole Limestones (Kinney, 1955, p. 30–31; Sando, 1967, 1977, 1979), Lodgepole equivalents in the Wasatch Range and western Uinta Basin (Baker, 1973), and the Whitmore Wash and Thunder Springs Members of the Redwall Limestone (McKee, 1979, p. 200–204) contain abundant brachiopods, corals, and foraminifera, indicating that these geologic units all are Lower Mississippian (Kinderhookian to Osagean). Fossil evidence indicates that the part of the Mission Canyon Limestone included in this hydrogeologic unit in the Overthrust Belt (Sando, 1979), the Mission Canyon equivalent in the Wasatch Range and Uinta Basin (Baker, 1973), the upper part of the Madison Limestone in the Uinta Mountains (Schell, 1969), and the Mooney Falls and Horseshoe Mesa Members of the Redwall Limestone (McKee, 1979) are Lower to Upper Mississippian (Osagean to Meramecian).

As a consequence of repeated marine incursions from the west, an eastward-rising sea floor during deposition, and uplift and erosion on the east as the Mississippian sea withdrew, the Redwall-Leadville zone generally becomes thinner eastward. The Redwall-Leadville zone decreases in thickness from a range of 1,300 to 2,500 ft on the west side of the area to less than 200 ft on the east side (pl. 11). Counter to this trend, however, the unit thins over the San Rafael Swell and Yampa Plateau, possibly as a result of syndepositional uplift, and thickens abruptly in a narrow belt extending northward from the Eagle Basin of Colorado to the Great Divide Basin of Wyoming. This thickening may be the result of either an anomalously high rate of sediment accumulation in a tectonically subsiding trough or the apparent result of post-depositional folding or faulting. Geologic units that comprise the Redwall-Leadville zone have been eroded from the central Uinta Mountains, White River Plateau, Sawatch Range, and San Juan Mountains and either were eroded from or never deposited in the Uncompahgre, Gunnison, and Defiance Plateaus, the Sneffels Horst, and the area east of the Park and Gore Ranges.

### COMPONENT GEOLOGIC UNITS

In the Overthrust Belt of Wyoming and western Gros Ventre Range, the Redwall-Leadville zone of the Madison aquifer consists of the Paine and Woodhurst Members of the Lodgepole Limestone (fig. 17) and the overlying Mission Canyon Limestone below the lowermost evaporite zone identified by Sando (1977) within the Mission Canyon Limestone. The Lodgepole Limestone and the part of the Mission Canyon Limestone that lies below the evaporite zones are about equally thick. The Paine Member of the Lodgepole Limestone consists of dark-gray, thinly bedded, silty and shaly, mostly fine grained, locally cherty limestone. The overlying Woodhurst Member consists of thinly bedded, dark-gray, alternately silty and fine-grained or oolitic and crinoidal, fossiliferous limestone (Sando, 1979, p. 5; Sando and Dutro, 1981). The Mission Canyon Limestone below the evaporite zones consists of thickly bedded, light-gray to bluish-gray, oolitic, crinoidal, crystalline limestone and thinly bedded, cherty, fine-grained dolomite and dolomitic limestone (Sando, 1977, p. 176; 1979, p. 8–10; Sando and Dutro, 1981).

According to Sando (1967, p. 532–533), changes in mineralogical composition, texture, bedding character, and marker beds prevent extending the stratigraphic nomenclature of the Overthrust Belt beyond its eastern margin. Thus, Mississippian carbonate rocks in Wyoming from the eastern

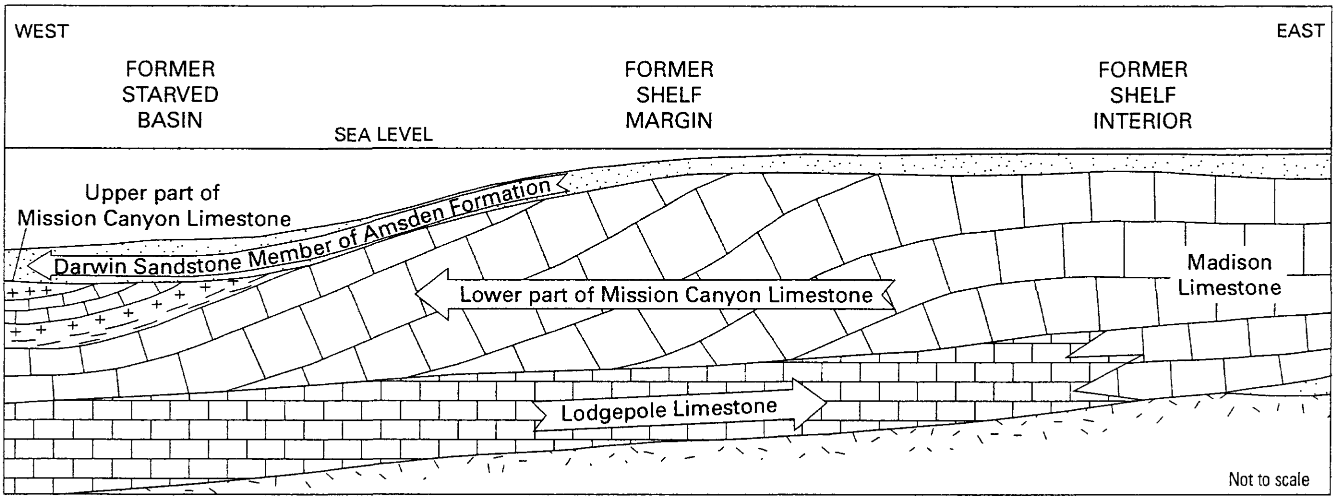



FIGURE 20.—Depositional model for Mississippian carbonate formations in Wyoming. Modified from Rose (1977, fig. 5); arrows indicate direction in which depositional environment of geologic unit progressed. The Darwin Sandstone is a member of the Amsden Formation.

Gros Ventre Range to the Rawlins Uplift and Sierra Madre are assigned to the Madison Limestone. As interpreted by Rose (1977), the Madison Limestone is a shallow-marine shelf deposit, and the Lodgepole Limestone is a shelf-margin deposit (fig. 20). The Mission Canyon Limestone was deposited over the former shelf margin as the sea withdrew at the end of Osagean time.

In the eastern Gros Ventre Range and Wind River Mountains, the Madison Limestone is divisible into six members (Sando, 1977, 1979, 1982). The lowest member, the Devonian and Lower Mississippian Cottonwood Canyon Member, is similar in lithology to the Darby Formation and is included with it in the Elbert-Parting confining unit. The uppermost member, the Bull Ridge Member, is similar in lithology to the Mission Canyon Limestone above the base of the evaporite zones and is included with this interval in the Darwin-Humbug zone of the Madison aquifer. The remaining members of the Madison Limestone are the Little Bighorn and Woodhurst Members (which are equivalent to the Lodgepole Limestone), the Big Goose Member, and the Little Tongue Member.

The Madison Limestone becomes increasingly more dolomitic from northwest to southeast along the Wind River Mountains as lower members pinch out and upper members thin because of erosion (Sando, 1967, p. 533). The stratigraphically lowest member in the Redwall-Leadville zone, the Little Bighorn Member is 49–102 ft thick and consists mostly of thickly bedded, crinoidal dolomite and dolomitic limestone. The overlying Woodhurst Member, 195–335 ft thick, consists mostly of thinly bedded, fine-grained to crystalline, pelletal and oolitic limestone and dolomitic limestone interbedded with dolomitic mudstone. Next in succession, the Big Goose Member is 210–328 ft thick and consists mostly of thickly bedded, cherty, fine- to coarse-grained, fossiliferous dolomite, dolomitic limestone, and subordinate limestone; beds commonly are shattered and brecciated. The uppermost member in the Redwall-Leadville zone, the Little Tongue Member, is 119–239 ft thick; it consists mostly of medium- to thick-bedded, cherty, fine- to coarse-grained, fossiliferous limestone and dolomite. An interval of solution breccia overlain by shattered and brecciated beds generally is present at the base of the Little Tongue Member but has been removed by erosion in the southeastern Wind River Mountains. Beds of red siltstone and sandstone are present in solution cavities throughout the Little Tongue Member.

From the southeastern Wind River Mountains east to the Rawlins Uplift and Sierra Madre, the Woodhurst, Big Goose, and Little Tongue Members make up most of the Madison Limestone (see Sando, 1967, fig. 3; 1979, fig. 5, section *A*–*A*′). In this area, the basal 5–35 feet of the Madison Limestone consists of sandstone, siltstone, and conglomerate (Thomas, 1951, p. 34; Keefer and Van Lieu, 1966, p. 33; Sando, 1967, p. 557; 1979, p. 12), that on the basis of sparse brachiopods may be equivalent to the Gilman Sandstone of Colorado, a deposit of probable Early Mississippian age. Similar deposits of sandstone and conglomerate between rocks of definite Cambrian and Madison lithologies in the western Uinta Mountains (Huddle and McCann, 1947b; Huddle and others, 1951) also may be a Gilman Sandstone equivalent.

In the Wasatch Range and western Uinta Basin, the Lodgepole equivalent consists in ascending order of (1) few inches to 20 ft of gray to brown, pebbly sandstone and sandy dolomite; (2) 100–260 ft of thinly to massively bedded, light- to dark-gray, vuggy dolomite; and (3) 500–900 ft of thinly to massively bedded, medium- to dark-gray, cherty limestone and dolomite that become more dolomitic toward the north, west, and south (Baker and Crittenden, 1961; Baker, 1964, 1972, 1973). The Mission Canyon equivalent consists of 375–585 ft of thickly to massively bedded, light- and dark-gray-banded, fine- to coarse-grained, cherty limestone and dolomite (Baker and Crittenden, 1961; Baker, 1964, 1972, 1973).

In general, the Madison Limestone of the Uinta Mountains is very similar in lithology to Mississippian deposits in the Overthrust Belt, Gros Ventre Range, and Wind River Mountains. As shown by Rose (1977, fig. 8), equivalents of the Lodgepole and Mission Canyon Limestones in the western Uinta Mountains grade eastward into a sequence of typical marine-shelf lithology. In the western Uinta Mountains, the Lodgepole equivalent ("the Madison or Gardison Limestone") consists predominantly of thinly bedded, dark-gray, fine-grained to crystalline, cherty limestone and dolomitic limestone with shale partings (Huddle and McCann, 1947b). The lower Mission Canyon equivalent ("the Deseret Limestone") consists of thickly bedded, light- to dark-gray and brown, fine-grained to crystalline, cherty limestone and dolomitic limestone (Huddle and McCann, 1947b; Huddle and others, 1951). In the eastern Uinta Mountains, the Madison Limestone (fig. 4) consists mostly of thickly to massively bedded, light- to dark-gray and tan, fine- to medium-grained, sparsely fossiliferous, locally dolomitic, and commonly cherty limestone (Kinney, 1955, p. 26; Ritzma, 1959, p. 22; Hansen and others, 1983). Shaly carbonate beds near the base can be traced into Colorado, where they are assigned to the Upper Devonian and Lower Mississippian(?) Dyer Dolomite (Hallgarth, 1959).

In northwestern Colorado, the Dyer Dolomite, Gilman Sandstone, and Leadville Limestone comprise the Redwall-Leadville zone. In the White River Plateau and southeastern Sawatch Range, the Dyer Dolomite consists mostly of gray, fossiliferous limestone overlain by gray, fine-grained to finely crystalline limestone and dolomite with shale interbeds and sparse chert (Dings and Robinson, 1957, p. 14; Bass and Northrop, 1963, p. 21–22). To the east and north, limestone layers become less numerous, and on the northeastern side of the Sawatch Range, the Dyer Dolomite consists almost entirely of dolomite (Campbell, 1972, p. 60; Tweto and Lovering, 1977, p. 27–28). Overlying the Dyer Dolomite in areas that probably were above the sea intermittently or adjacent to land masses at the time of deposition is the Gilman Sandstone (De Voto, 1980a, p. 58). In the Sawatch Range, the Gilman Sandstone consists of yellow and light-gray, fine- to medium-grained sandstone, sandy dolomite, and limestone-chert-sandstone breccia that, together, commonly are less than 25 ft thick (Nadeau, 1972, p. 86; Tweto and Lovering, 1977, p. 29–30; Bryant, 1979, p. 21). According to Bass and Northrop (1963, p. 26–27) and Conley (1972, p. 107–108), a 15- to 30-ft-thick interval at the base of the Leadville Limestone in the White River Plateau that consists of sandy dolomite with local interbeds of dolomitic sandstone and chert breccia probably is equivalent to the Gilman Sandstone. The Leadville Limestone in northwestern Colorado (fig. 21) typically consists of thinly bedded, medium- to dark-gray, fine- to medium-grained, locally cherty limestone and dolomite overlain by thickly to massively bedded, light-gray and bluish-gray, finely to coarsely crystalline, oolitic limestone (Dings and Robinson, 1957; Bass and Northrop, 1963; Conley, 1972; Nadeau, 1972; Bryant, 1979; De Voto, 1980a). The upper facies forms about one-half to two-thirds of the formation. At the northeastern end of the Sawatch Range, the upper facies has been altered hydrothermally into vuggy, dark-gray and white banded or pearly-white dolomite (Tweto and Lovering, 1977, p. 30–32).

In southwestern Colorado, southeastern Utah, and northeastern Arizona, the equivalent of the Dyer Dolomite is the Ouray

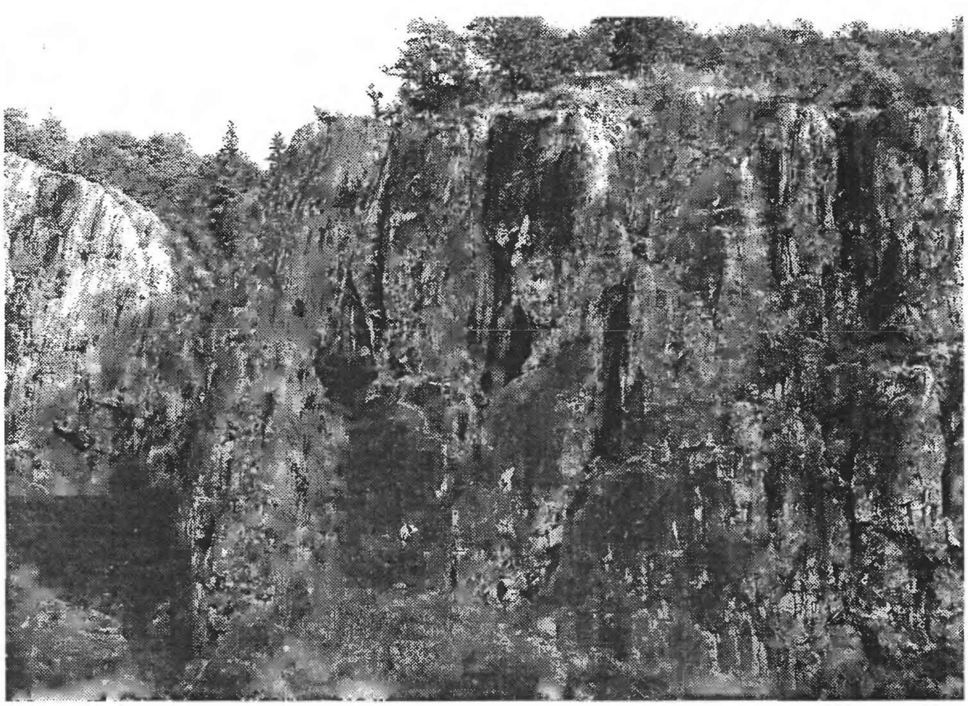


FIGURE 21.—Cavernous Mississippian Leadville Limestone in Glenwood Canyon at Glenwood Springs, Colo. Large thermal springs discharge from the formation in this area.

Limestone. This formation typically consists of gray, tan, or beige, shaly or sandy limestone and dolomite with interbeds of green and gray, waxy shale (Baars and Knight, 1957, p. 121; Cooper, 1960, p. 76; Baars and others, 1987, p. 346). In most areas, an interval of green or gray waxy shale as much as 15 ft thick separates the Ouray Limestone from overlying Mississippian rocks (Parker and Roberts, 1963, p. 41).

The Ouray Limestone is overlain in southwestern Colorado by the Leadville Limestone and to the west, in Arizona and Utah, by the Redwall Limestone. Consistent with its lithology farther north, the Leadville Limestone, where it crops out in the San Juan Mountains, consists of a thin interval of limestone and dolomite overlain by massively bedded, oolitic, bioclastic, crystalline limestone (Baars and Knight, 1957, p. 121; De Voto, 1980a, p. 59–63; Baars and others, 1987, p. 346). In the subsurface of the Paradox Basin and Four Corners area, however, the Leadville Limestone becomes increasingly more dolomitic and cherty westward and grades into the Redwall Limestone.

In northeastern Arizona and southeastern Utah, the Redwall Limestone (fig. 2) consists of four alternately transgressive and regressive sequences, which McKee (1963, 1979) designated the Whitmore Wash, Thunder Springs, Mooney Falls, and Horseshoe Mesa Members. The Whitmore Wash Member consists of thinly bedded, fine-grained dolomite and thickly bedded, bioclastic, and oolitic limestone and dolomite. The Thunder Springs Member consists of thin-bedded, fine-grained dolomite, bioclastic and pelletal limestone, and bedded chert, which locally is replaced by anhydrite. From south to north, dolomite layers in the Thunder Springs Member increase in abundance and gradually become the only carbonate rock type present. The Mooney Falls Member, the thickest part of the Redwall Limestone, consists of thickly to massively bedded, locally cherty, limestone and dolomite layers that alternately are fossiliferous, stromatolitic, oolitic, or fine grained. The uppermost member, the Horseshoe Mesa Member, grades northwestward from thinly bedded, commonly stromatolitic or oolitic, fine-grained limestone to cherty dolomite.

## CONTACTS

The Redwall-Leadville zone of the Madison aquifer overlies rocks of Precambrian to Late Devonian age (Mallory, 1979, p. 209). In southwestern Wyoming, Mississippian carbonate rocks progressively overlie Devonian, Ordovician, Cambrian, and Precambrian rocks from west to east (fig. 22). From the Wasatch Range to the Duchesne River area of the western Uinta Mountains, the Mississippian rocks cut progressively deeper into the Cambrian depositional sequence (Huddle and McCann, 1947b; Baker, 1964, 1973). South and east of the Uinta Basin, predominantly Upper Devonian carbonate rocks generally rest on older Devonian carbonate and clastic rocks (Mallory, 1979, pl. 2), indicating only a slight hiatus prior to deposition of rocks that comprise the Redwall-Leadville zone.

The predominantly Upper Devonian carbonate rocks are overlain either by the Gilman Sandstone and basal sandstone layers in the Madison Limestone or by Mississippian carbonate rocks. The Gilman Sandstone unconformably overlies the Dyer Dolomite in the vicinity of the Sawatch Range but disconformably overlies it to the west (Bass and Northrop, 1963, p. 26; Tweto and Lovering, 1977, p. 28; De Voto, 1980a, p. 61). Where a basal sandstone is present in the Madison Limestone, it generally rests unconformably on Cambrian rocks (Huddle and others, 1951; Ritzma, 1951, p. 66). Where the Gilman Sandstone has been removed by erosion, as in the southern Sawatch Range, the contact between the Dyer Dolomite and Leadville Limestone is an unconformity with as much as 30 ft of relief (Dings and Robinson, 1957, p. 15; Nadeau, 1972, p. 81). The Leadville Limestone unconformably overlies the Ouray Limestone in the San Juan Mountains but grades into it in the Paradox Basin to the west (De Voto, 1980a, p. 59–60). The Redwall Limestone unconformably overlies the Ouray Limestone in southeastern Utah (Cooper, 1960, p. 76) and the Temple Butte Formation in the Grand Canyon area of northeastern Arizona (McKee, 1969, p. 44).

Within the Mississippian sequence, contacts between formations or members of formations generally are conformable or disconformable (see, for example, McKee, 1979, p. 203). However, the contact between the Gilman Sandstone and Leadville Limestone is an unconformity (Tweto and Lovering, 1977, p. 28; De Voto, 1980a, p. 61).

The upper surface of the Redwall-Leadville zone is an unconformity that progressively truncates older rocks from west to east across the region. North of the Uinta Mountains, from the Overthrust Belt to the Rock Springs Uplift, the Upper Mississippian Darwin Sandstone Member of the Amsden Formation unconformably overlies a progressively thinner interval of Upper Mississippian rocks at the top of the Mission Canyon and the Madison Limestones; east of the Rock Springs Uplift, the Darwin Sandstone Member rests on Lower Mississippian layers in the Madison Limestone (Sando, 1967, fig. 3; 1979, fig. 5). Similarly, from the Wasatch Range east to the eastern Uinta Mountains, the Upper Mississippian Humbug Formation rests on strata in the Deseret and Madison Limestones that progressively increase in age from Late to Early Mississippian. South and east of the Uinta Mountains, an erosional surface overlain by the Lower Pennsylvanian Molas Formation cuts progressively deeper into the Redwall and Leadville Limestones from west to east. The uppermost layers of the Redwall Limestone, on the west, are Upper Mississippian, whereas the uppermost layers of the Leadville Limestone, on the east, are Lower Mississippian. In the eastern Gore Range and western San Juan Mountains, the Molas Formation rests on Upper Devonian rocks. Thus, from west to east, formations forming the top of the Redwall-Leadville zone increase in age from Late Mississippian to Late Devonian. Coincident with deepening of the erosional surface, relief on the surface increases from a few feet in the western part of the region to more than 100 ft in the

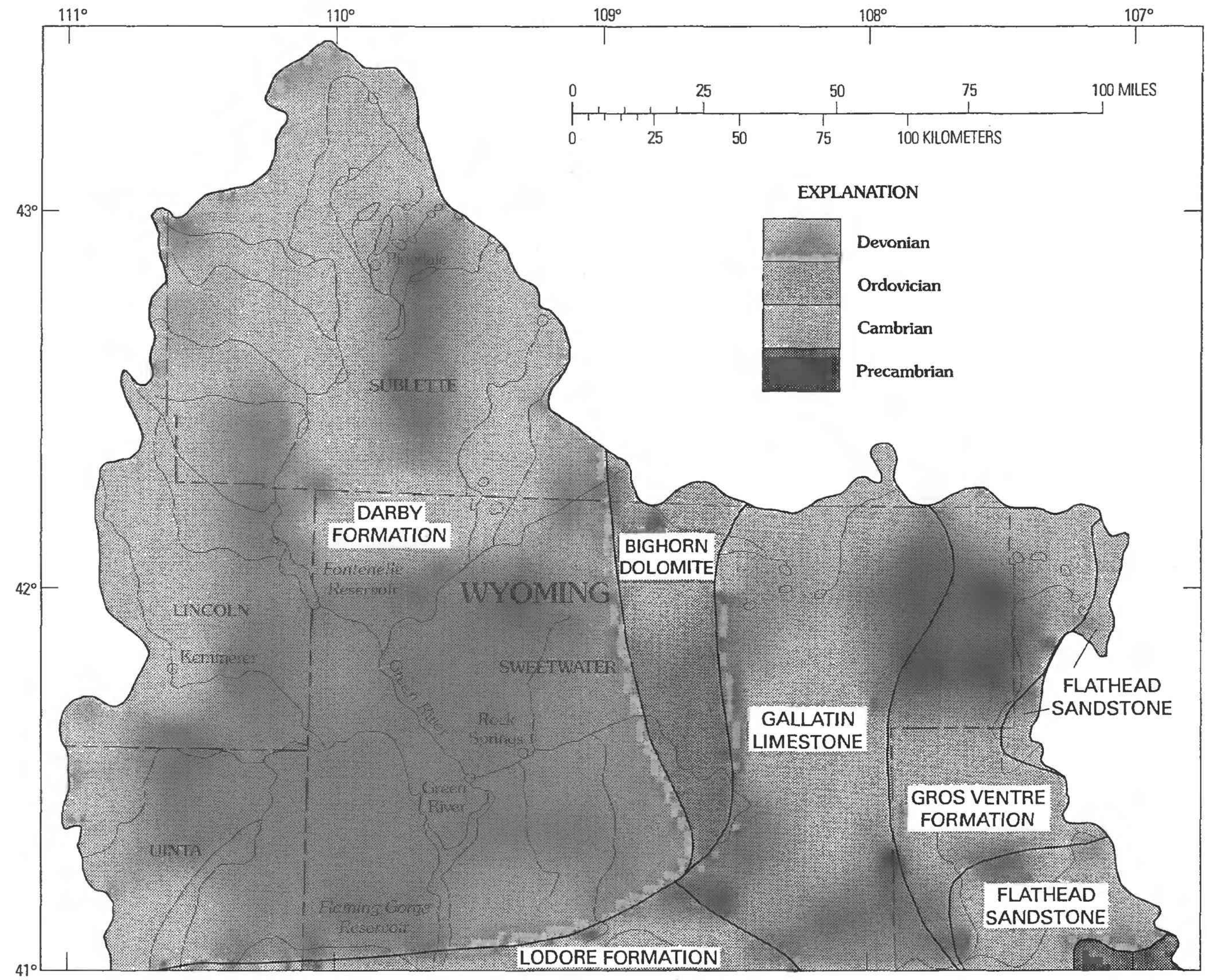



FIGURE 22.—Pre-Mississippian geology in Wyoming. Geologic units in contact with overlying Mississippian rocks are shown.

eastern part (Keefer and Van Lieu, 1966, p. 33; McKee, 1969, p. 46; De Voto, 1980a, p. 68–69). Where the Mississippian rocks have been deeply eroded, a rubble of carbonate blocks, sand, and red clay and silt fills caverns and solution-widened fractures as much as 100 ft below the erosional surface.

### DARWIN-HUMBUG ZONE

The Darwin-Humbug zone of the Madison aquifer (pl. 12) consists of carbonate and clastic rocks that accumulated at the close of the Mississippian during the transition from a regressing to a transgressing sea (Craig, 1972; Kent, 1972). Component geologic units are characteristic of a fluctuating but generally shallow marine environment (fig. 20). Component geologic units include the Humbug Formation, the Bull Ridge Member of the Madison Limestone, the Mission Canyon Limestone above the base of the lowest evaporite zone (referred to as the upper part of the Mission Canyon Limestone in this report), and the Darwin Sandstone Member of the Amsden Formation (table 1 and pl. 5). Paleontological data (Sando, 1979, p. 9–12) indicate that the upper part of the Mission Canyon Limestone and the Bull Ridge Member of the Madison Limestone are Lower to Upper Mississippian (upper Osagean to Meramecian). The Darwin Sandstone Member is unfossiliferous (Sando and others, 1975, p. 20), and the Humbug Formation contains poorly preserved, nondiagnostic fossils (Huddle and McCann, 1947b; Kinney, 1955, p. 31; Schell, 1969, p. 145). Nevertheless, both the Darwin Sandstone Member and the Humbug Formation are believed to be Upper Mississippian (Meramecian to Chesterian) on the basis of their stratigraphic position between datable formations (Sando and others, 1975, p. 21; Mallory, 1979, p. 214–216).

The Darwin-Humbug zone is thin and has the most restricted occurrence of the hydrogeologic units composed of Paleozoic rocks in the UCRB. The Darwin-Humbug zone occurs only in and near the Great Divide Basin, the north flank of the Wind River Mountains, the Gros Ventre Range, the Overthrust Belt, the Uinta Mountains, and the Uinta Basin. The Darwin-Humbug zone is less than 200 ft thick in the Wind River Mountains and Great Divide Basin, but it is 500 to more than 700 ft thick in depositional centers within the Gros Ventre Range and Overthrust Belt and nearly 800 ft thick in the western Uinta Mountains and northwestern Uinta Basin. Lateral and vertical gradation into the Madison Limestone and the lower part of the Mission Canyon Limestone and erosion during Cretaceous and Tertiary uplift of the Uinta Mountains limit the areal extent of the Darwin-Humbug zone.

### COMPONENT GEOLOGIC UNITS

In the Uinta Mountains and Uinta Basin, which take in most of the extent of the Darwin-Humbug zone, rocks comprising the hydrogeologic unit are assigned to the Humbug Formation. The Humbug Formation in the eastern Uinta Mountains (fig. 4) typically consists of interbedded limestone and sandstone with some shale layers (see Untermann and Untermann, 1954, p. 30–31; Kinney, 1955, p. 28; Hansen, 1965b, p. 40; Hansen and others, 1983). Sandstone layers characteristically are reddish brown, tan, yellow, white, and gray, fine grained to medium grained, and cemented by silica, calcite, or hematite. Limestone layers are gray to bluish gray, fine grained, and commonly brecciated; locally they contain nodules and lenses of chert. Shale layers are gray, red, and black; locally they are limy. In the western Uinta Mountains, the Humbug Formation consists of brecciated sandstone and limestone, with sandstone breccias grading laterally into limestone breccias (Huddle and McCann, 1947b; Huddle and others, 1951). The sandstone breccias are white and gray, fine grained, and cemented by calcite; limestone breccias are light gray and brown, fine grained, and sparsely cherty. In the Wasatch Range above and below the Charleston Thrust Fault (the leading edge of the Overthrust Belt) and, presumably, in the western Uinta Basin, the Humbug Formation consists of light- to dark-gray, cherty limestone with dolomitic layers interbedded with buff to gray, fine- to medium-grained, limy to quartzitic sandstone (Baker and Crittenden, 1961; Baker, 1964). In the southwestern Uinta Basin, the Humbug Formation in boreholes consists of light-gray, tan, and beige sandstone and limestone with some intervals of dolomite, dark-gray, green, tan, and red siltstone and sandstone, and, locally, anhydrite. Anhydrite layers can comprise as much as 11 percent of the formation. Throughout its area of occurrence, the Humbug Formation characteristically is thinly to thickly bedded.

In southwestern Wyoming, the lower part of the Humbug Formation grades laterally into either the upper part of the Mission Canyon Limestone or the Bull Ridge Member of the Madison Limestone (as used by Sando, 1977, 1979). Prior to establishment of the Bull Ridge Member, strata included in this interval were variously assigned to the upper part of the Brazer Limestone and lower part of the Amsden Formation (Foster, 1947), Sacajawea Formation (Branson and Branson, 1941), Sacajawea Member of the Madison Limestone (Sando, 1967), or upper member of the Madison Limestone (Keefer and Van Lieu, 1966). The upper part of the Humbug Formation grades laterally into the Darwin Sandstone Member of the Amsden Formation (fig. 23).

The upper part of the Mission Canyon Limestone in the Salt River Range, Wyoming Range, and western Gros Ventre Range consists of limestone, dolomite, and solution breccia, with interbeds of red shale in the upper part of the interval (Foster, 1947, p. 1556–1557; Wanless and others, 1955, p. 22–31; Sando, 1977, p. 176). The limestone and dolomite generally are gray and pink, fine grained to finely crystalline, and cherty. The solution breccias are concentrated at the bottom and top of the stratigraphic interval (Sando, 1977, pl. 1); they consist of blocks and fragments of limestone and dolomite in a matrix of sandstone and siltstone (see Sando and Dutro, 1981, Haystack Peak section). The breccias apparently resulted from collapse following dissolution of gypsum interbeds, which are preserved in Hoback Canyon at the northern end of the Hoback Range. In the Hoback Canyon area, the upper part of the Mission Canyon Limestone contains a third solution breccia interval and, atypically, numerous interbeds of red and green gypsiferous shale (Wanless and others, 1955, p. 27–29; Sando, 1977, pl. 1).

East of the Overthrust Belt and western Gros Ventre Range, the upper part of the Mission Canyon Limestone grades into the Little Tongue and Bull Ridge Members of the Madison Limestone (Sando, 1977, pl. 1). The contact between these two members of the Madison Limestone was placed by Sando (1977) at the base of the upper of two solution breccia intervals, the lateral equivalent of the middle solution breccia interval in the Mission Canyon Limestone. The Little Tongue Member, a component geologic unit of the Redwall-Leadville zone, was described previously. The Bull Ridge Member consists of a basal solution breccia interval, a medial limestone collapse breccia interval, and an upper interval of undisturbed limestone, dolomite, and siltstone (Sando, 1967, p. 539). The lower solution breccia interval consists of chaotically bedded, red and yellow mudstone, siltstone, and sandstone with angular fragments of limestone, dolomite, and chert, that become progressively larger upward in the interval (Sando, 1967, p. 538). In the collapse breccia interval, blocks of fine-grained, bioclastic limestone tens of feet in diameter and rotated only slightly out of original bedding attitude lie in a matrix of Darwin-like sandstone (Sando, 1967, p. 539). Above the collapse breccia interval, the carbonate rocks consist of gray and tan, thin- to medium-bedded, fine-grained to pelletal, locally stromatolitic or cherty limestone and dolomite (Keefer and Van Lieu, 1966, p. 30; Sando, 1967, p. 539; 1979, p. 12). Throughout the Bull Ridge Member, sinkholes and solution cavities filled with quartz sandstone and shale

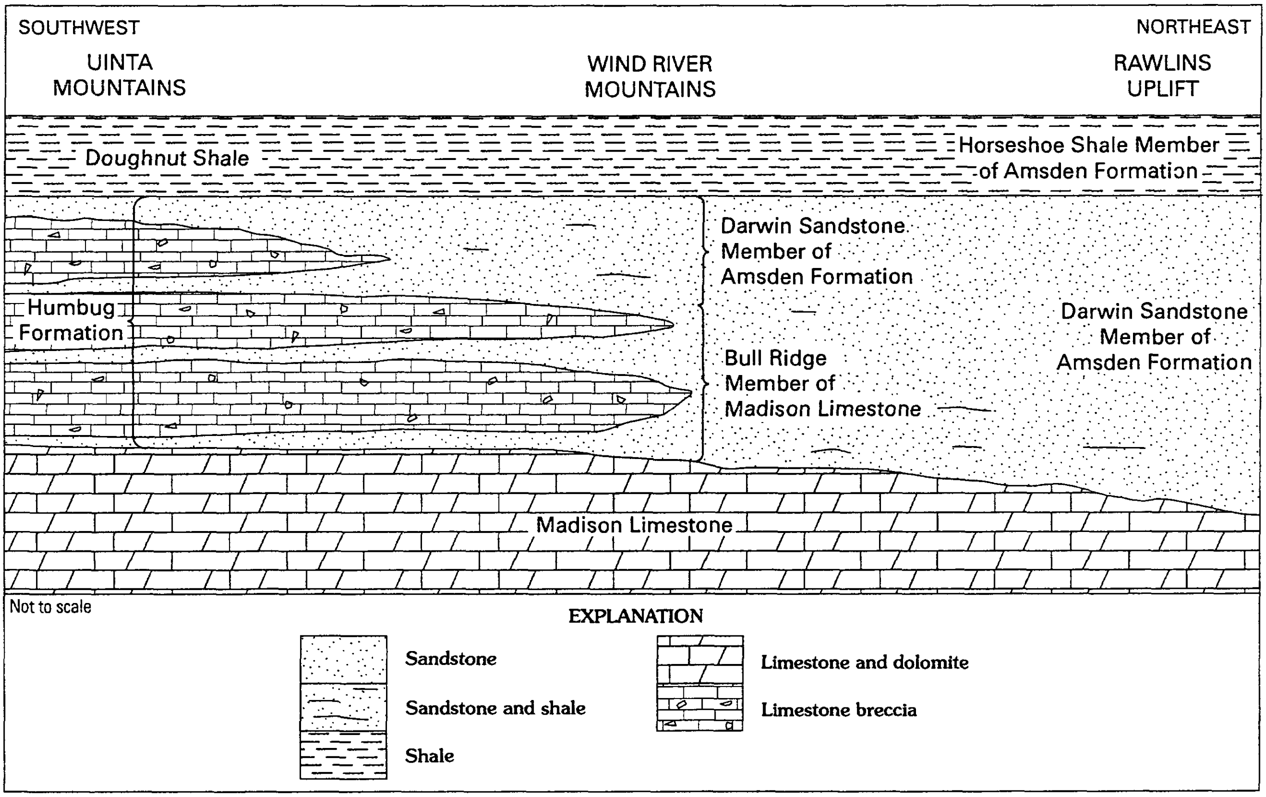



FIGURE 23.—Schematic section showing stratigraphic relations in the Darwin-Humbug zone of the Madison aquifer. Horizontal distance is about 200 miles.

related to deposition of the overlying Amsden Formation occur (Sando, 1967, p. 539).

The Darwin Sandstone Member of the Amsden Formation, in general, consists of thinly to massively bedded, gray, white, beige, and red, fine- to medium-grained, quartz sandstone that commonly is crossbedded (Sando and others, 1975, p. 20; Maughan, 1979, p. 27). The rock is weakly to moderately well cemented by calcite in most areas; locally, as in the Overthrust Belt, it is quartzitic (Wanless and others, 1955, p. 32). Thin interbeds of shale and carbonate rocks are present locally. Angular blocks and fragments of limestone occur in the sandstone above the contact with the Madison and Mission Canyon Limestones in most places (Maughan, 1979, p. 27). Because the Darwin Sandstone Member was deposited on a hummocky karst surface, abrupt changes in thickness occur from place to place (Mallory, 1967, p. 6). In some areas, the Darwin Sandstone Member is present only in caverns and sinkholes (Mallory, 1967); in other areas, it is more than 300 ft thick.

### CONTACTS

Geologic units that comprise the Darwin-Humbug zone of the Madison aquifer grade down into the parts of the Madison and Mission Canyon Limestones that are in the Redwall-Leadville zone of the Madison aquifer. Geologic units in the Darwin-Humbug zone are overlain conformably by the Doughnut Shale and the Horseshoe Shale Member of the Amsden Formation of Mississippian and Pennsylvanian age (Huddle and others, 1951; Baker and Crittenden, 1961; Keefer and Van Lieu, 1966, pl. 2; Sando and others, 1975, p. 21). Internally, an unconformity separates the Darwin Sandstone Member of the Amsden Formation from the underlying Mission Canyon Limestone (Wanless and others, 1955, p. 12) and Bull Ridge Member of the Madison Limestone (Sando, 1967, fig. 3; Sando and others, 1975, pl. 4). In the area of the Rawlins Uplift, between the southeastern end of the Wind River Mountains and the northwestern end of the Sierra Madre, the Bull Ridge Member has been removed entirely by erosion, and the Darwin Sandstone Member of the Amsden Formation unconformably overlies the Little Tongue Member of the Madison Limestone. A disconformity near the top of the Humbug Formation noted by Ritzma (1959, p. 23) may be the lateral continuation of the pre-Darwin unconformity.

## FOUR CORNERS CONFINING UNIT

A widespread confining unit in the UCRB separates the Madison and underlying aquifers from Pennsylvanian and Permian rocks that comprise the Canyonlands aquifer. This confining unit is named the Four Corners confining unit in this report, as a symbol of its hydrologic importance in the four States joined at the Four Corners—Arizona, Colorado, New Mexico, and Utah. The Four Corners confining unit is divisible vertically into two subunits with different lithologic and hydrologic properties. The lower subunit, which consists of shale with subordinate carbonate rocks and relatively minor sandstone and gypsum, is called the Belden-Molas subunit, after the two formations that comprise the zone in northwestern Colorado and typify the range in lithology within. The upper subunit, which is characterized by thick deposits of gypsum, anhydrite, and halite, is called the Paradox–Eagle Valley subunit, after the two geologic units that contain most of the evaporite deposits within the interval.

#### BELDEN-MOLAS SUBUNIT

The Belden-Molas subunit of the Four Corners confining unit (pl. 13) consists of formations and members of formations predominantly composed of black and red shale that were deposited on eroded Mississippian carbonate and clastic rocks, at first subaerially and later subaqueously, as a fourth Paleozoic sea advanced across the area (Kent, 1972; Mallory, 1972). Component geologic units include the Horseshoe Shale Member of the Amsden Formation, Doughnut Shale (Formation), Molas Formation, Belden Formation, lower member of the Hermosa Formation (Pinkerton Trail Formation of Wengerd and Strickland, 1954), Surprise Canyon Formation (of Billingsley and Beus, 1985), and Watahomigi Formation (table 1 and pl. 5). Because of lithologic similarity, component geologic units are delimited primarily along axes of thinning between depositional centers.

Although the name "Manning Canyon Shale" has been applied to rocks equivalent to the Doughnut Shale in the central and western Uinta Mountains (Ritzma, 1959; Schell, 1969, p. 146), mapping in the Wasatch Range (Baker and Crittenden, 1961; Baker, 1964, 1972, 1973) indicates that the Manning Canyon Shale is restricted to the upper plate of the Charleston Thrust Fault, where it occurs between the Upper Mississippian Great Blue Limestone and the Pennsylvanian and Permian Oquirrh Formation. Recent drilling in the Wasatch Range just west of the UCRB, at SLD 05-05-11bb, indicates that the Great Blue Limestone and Manning Canyon Shale do not extend into the UCRB (Bruce Bryant, U.S. Geological Survey, oral commun., 1990). However, strata, equivalent in lithology and age to the upper part of the Great Blue Limestone and the lower part of the Manning Canyon Shale, extend beneath the thrust plate from the Wasatch Range to the UCRB. In the Wasatch Range the autochthonous rocks are called the "Doughnut Formation." Hence, the name "Doughnut Shale" is extended from the eastern Uinta Mountains, where Hansen and others (1983) used the name unequivocally, into the remainder of the Uinta Mountains and the Uinta Basin, and the name "Manning Canyon Shale" is not used in the UCRB in this report.

Abundant paleontological evidence (mainly brachiopods, pelecypods, gastropods, corals, bryozoans, and foraminifera) indicates that component formations become younger from west to east across the area. Fossils collected in the Wasatch Range and Uinta Mountains indicate that the lower part of the Doughnut Shale is Upper Mississippian (Chesterian); the unfossiliferous upper part of this formation may be Lower Pennsylvanian (Huddle and others, 1951; Kinney, 1955, p. 35–36; Ritzma, 1959, p. 23–25; Baker, 1964). The Horseshoe Shale Member of the Amsden Formation decreases in age from Late Mississippian to Early Pennsylvanian (Morrowan) eastward across Wyoming (Sando and others, 1975, p. 24–25). In Colorado, the Molas Formation is Upper Mississippian and Lower Pennsylvanian (Chesterian to Morrowan) in the western part of its depositional area and Lower to Middle Pennsylvanian (Morrowan to Desmoinesian) in the eastern part (Wengerd, 1957, p. 135; Merrill and Winar, 1961, p. 87; Bass and Northrop, 1963, p. 30; Tweto and Lovering, 1977, p. 33–35). Overlying the Molas Formation, the Belden Formation in northwestern Colorado is Lower Pennsylvanian (Morrowan) on the west and Middle Pennsylvanian (Atokan) on the east (Dings and Robinson, 1957, p. 17–18; Bass and Northrop, 1963, p. 40–41; Tweto and Lovering, 1977, p. 35–38); the lower member of the Hermosa Formation is Middle Pennsylvanian (Atokan and Desmoinesian) in southwestern Colorado (Wengerd, 1958, p. 118). The Surprise Canyon and Watahomigi Formations in northeastern Arizona comprise an Upper Mississippian to Middle Pennsylvanian (Chesterian to Atokan) sequence (McKee, 1982, p. 37; Billingsley and Beus, 1985, p. 31). The spatial distribution of the formations that comprise the Belden-Molas subunit indicates that the fourth Paleozoic sea encroached from the west in Late Mississippian time and spread eastward during Early and Middle Pennsylvanian time.

The Belden-Molas subunit thickens and thins erratically (pl. 13) as a result of irregularities in the depositional surface, lateral gradation into other Mississippian and Pennsylvanian geological units, and, to some degree, erosion associated with Pennsylvanian-Permian and Laramide uplifts. The Horseshoe Shale Member of the Amsden Formation in Wyoming and the Surprise Canyon and Watahomigi Formations in Arizona and southeastern Utah generally are less than 200 ft thick. The Doughnut Shale, although thinned locally by uplift of the Uinta Mountains, Axial Basin Arch, and Rock Springs Uplift, generally thickens toward depositional centers in the Washakie Basin and the Utah salient of the Overthrust Belt. The Doughnut Shale is more than 400 ft thick in its eastern depositional center and 1,200–1,300 ft thick at the western edge of the UCRB. In the southern UCRB, the Molas Formation and lower member of the Hermosa Formation thicken toward a trough that meanders around the western edges of the Uncompahgre Plateau and Paradox Basin. Maximum thicknesses in the center of this trough generally are between 800 and 900 ft. However, the Belden Formation, where it crops out in northwestern Colorado, can be as much as 1,000 ft thick (Bass and Northrop, 1963, p. 31–34); in the subsurface, this formation is 1,000–4,300 ft thick (the maximum known thickness occurs in the American Quasar 1-9 Benton well, SC02-85-0966). The Belden-Molas subunit is absent throughout most of Wyoming, the central UCRB, and the eastern and western margins of the UCRB.

### COMPONENT GEOLOGIC UNITS

North of the Rock Springs Uplift in Wyoming, from the Overthrust Belt to the Rawlins Uplift, rocks comprising the Horseshoe Shale Member of the Amsden Formation are assigned to the Belden-Molas subunit. As described by Sando and others (1975, p. 23–24), the Horseshoe Shale Member generally consists of fissile, red, gray, and purple sandy siltstone and mudstone with thin beds of fine-grained calcareous sandstone and silty, sandy, or shaly limestone and dolomite. The carbonate and sandstone layers locally exceed the shale layers in abundance. According to Mallory (1967, p. 12–13), beds of pisolitic hematite or hematitic bauxite as much as 3 ft thick commonly occur in the lower part of the member.

From the vicinity of the Rawlins Uplift south to the Uinta Basin, strata equivalent to the Horseshoe Shale Member are assigned to the Doughnut Shale (fig. 4). In general, the Doughnut Shale of the eastern and central Uinta Mountains consists of red shale and sandstone overlain by black to dark-gray carbonaceous shale containing interbeds of greenish sandstone, green and tan sandy limestone, black shaly limestone, and bituminous coal (Untermann and Untermann, 1954; Kinney, 1955; Hansen, 1965b; Hansen and others, 1983). Similarly, in the western Uinta Mountains, the Doughnut Shale in ascending order consists of (1) red, purple, and maroon shale with some interbedded limestone and quartzitic to pebbly sandstone; (2) fissile, dark-gray to black shale with some interbedded limestone; and (3) interbedded gray shale and limestone with minor sandstone (Huddle and McCann, 1947a). Limestone layers increase westward; the Doughnut Shale in the Wasatch Range and western Uinta Basin consists of dark-gray to black shale with thin interbeds of rusty-weathering, gray, fine-grained, quartzitic sandstone and quartzite overlain by thinly bedded, black limestone with shale interbeds (Baker and Crittenden, 1961; Baker, 1964). At the southwestern edge of the Uinta Basin, the Doughnut Shale in ascending order generally consists of (1) red, purple, and maroon mudstone and siltstone with limestone interbeds; (2) dark-gray, black, and brown shale with interbedded limestone and gray, brown, and white sandstone; and (3) interbedded greenish-gray, gray, and black shale and limestone with minor sandstone and coal.

At the southern edge of the Sand Wash Basin and the southern and eastern edges of the Uinta Basin, the Doughnut Shale grades into the Molas and Belden Formations (fig. 24). The Molas Formation in northwestern Colorado typically is a discontinuous deposit of poorly stratified purplish-red and ochre-colored claystone and siltstone containing nodules and boulders of limestone and chert; thicknesses range from inches to 130 ft (Bass and Northrop, 1963, p. 30; De Voto and others, 1986, p. 39). On the northeast flank of the Sawatch Range, however, the Molas Formation has been altered to gray carbonaceous shale and white conglomeratic sandstone (Tweto and Lovering, 1977, p. 33). Similarly, the Molas Formation in the Rico Mountains of southwestern Colorado (see pl. 1 for location) is a pebbly quartzite, locally called the Larsen Quartzite (McKnight, 1974, p. 13–16). Elsewhere in southwestern Colorado, the Molas Formation (fig. 25) consists of unstratified fragments of limestone and chert in a matrix of red silt and clay overlain by poorly to well-stratified red to varicolored shale and limy shale with lenses and interbeds of sandstone and limestone; the total thickness ranges from 0 to about 150 ft (Wengerd, 1957, p. 118; Merrill and Winar, 1961, p. 83–88; Baars and others, 1987, p. 347). This characteristic lithology continues throughout southeastern Utah and northeastern Arizona wherever the Molas Formation is identifiable (see, for example, Heylmun, 1958, p. 1789; Irwin and others, 1971, p. 20–21).

Overlying the Molas Formation in northwestern Colorado is the Belden Formation. The Belden Formation (fig. 26), typically consists of fissile, black to dark-gray, micaceous mudstone and siltstone with interbedded limestone and dolomite (Brill, 1944, p. 624–627; Bass and Northrop, 1963, p. 31–41; Tweto and Lovering, 1977, p. 34–38). Carbonate layers exceed shale layers toward the center of the Belden Formation's depositional area (pl. 13). Gypsum and anhydrite generally are not present, but they comprise 1–6 percent of the rocks in a northwest-trending belt north of the White River Plateau and in the vicinity of Ruedi Dam. Beds of gray, black, brown, and green, micaceous sandstone and orange, arkosic conglomerate are present, particularly around the margins of the depositional area, where they comprise 10–30 percent of the formation. Thickening of the Belden Formation in a belt trending northwest from the vicinity of Eagle, Colo., to the Danforth Hills in part is related to thick intervals of arkosic sandstone concentrated in the lower part of the formation. Characteristically, the shale within this belt is maroon, red, and purple, as well as black and gray. The sandstone and reddish shale are interpreted to be pulses of terrigenous sediment eroded from the ancestral Front Range Uplift, to the north and east. The Molas and Belden Formations in the vicinity of the Colorado-Utah State line atypically consist entirely of red, maroon, and purple shale with sandstone and carbonate interbeds that are interpreted to be of mostly terrigenous or tidal-flat origin.

The Molas Formation in southwestern Colorado, southeastern Utah, and northeastern Arizona, from the Uinta Basin to the Kaibab Plateau, is overlain by the lower member of the Hermosa Formation. The lower member of the Hermosa Formation generally consists of gray, crystalline to sandy, fossiliferous limestone interbedded with and underlain by greenish-gray, dark-gray, and black shale (fig. 27); locally, the unit contains interbeds of red shale, sandstone, or limestone conglomerate (Wengerd, 1958, p. 115; Baars and others, 1987, p. 347). Stratigraphic relations among Pennsylvanian and Permian formations in southeastern Utah are shown in figure 28.

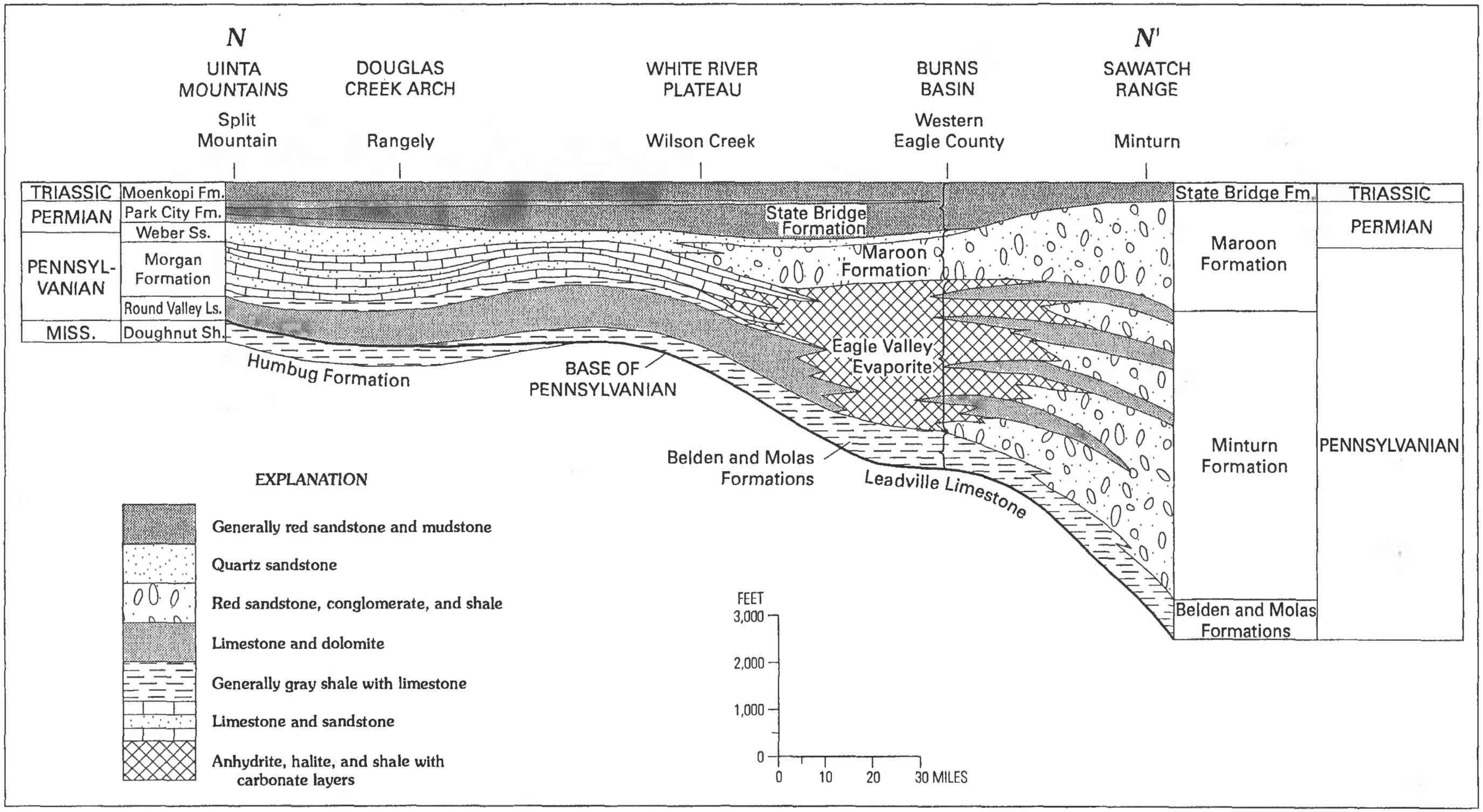



FIGURE 24.—Stratigraphic section showing relations among Pennsylvanian and Permian formations in northwestern Colorado. Modified from De Voto (1980b, fig. 6); location of section shown on plate 13.

FIGURE 25.—Pennsylvanian Molas Formation at its type locality, Molas Lake, in the San Juan Mountains, Colo.

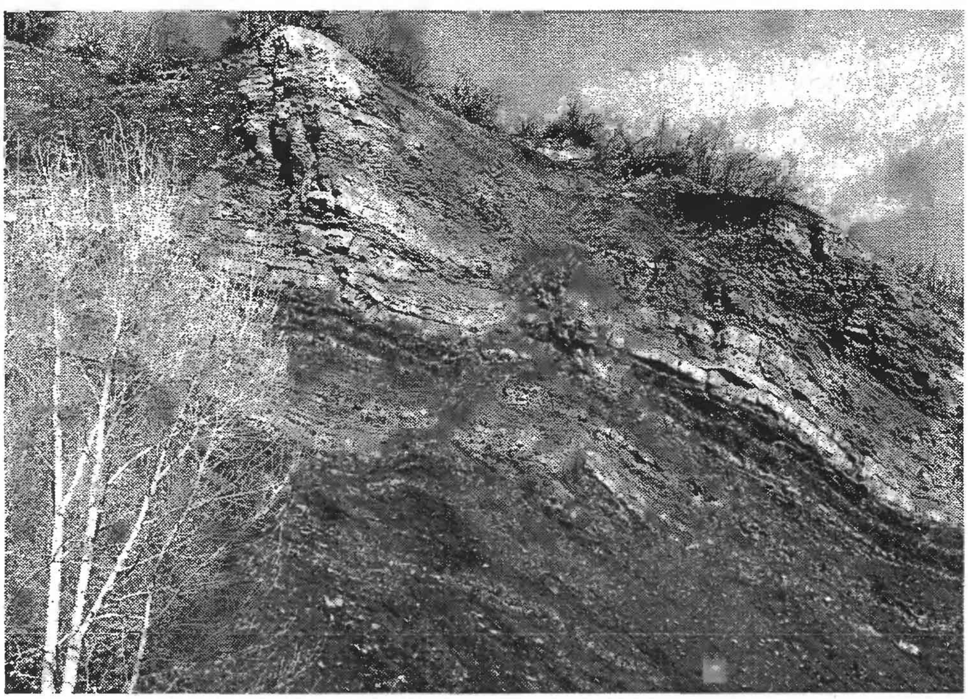


FIGURE 26.—Pennsylvanian Belden Formation at Ruedi Reservoir on the Fryingpan River southeast of Glenwood Springs, Colo. The formation here consists of shale with thin limestone interbeds.

In the vicinity of the Marble Platform and Kaibab Plateau, the Molas Formation and lower member of the Hermosa Formation grade into the Surprise Canyon Formation and the Watahomigi Formation of the Supai Group (fig. 2). The Surprise Canyon Formation, which occurs as channel fillings in the Redwall Limestone, consists of red-brown, brown, and gray, medium- to coarse-grained sandstone, limestone-chert conglomerate, coarse-grained limestone, and siltstone. The thickness of these rocks ranges from 0 to 80 ft in the eastern Grand Canyon and Marble Canyon. The Watahomigi Formation in Marble Canyon consists of red and reddish-brown mudstone and siltstone with interbedded gray and red, fine-grained, jasper-bearing limestone and dolomite and a basal conglomerate interval. The basal conglomerate consists of chert pebbles in a matrix of reddish-orange, very fine grained sandstone or siltstone. The Watahomigi Formation is

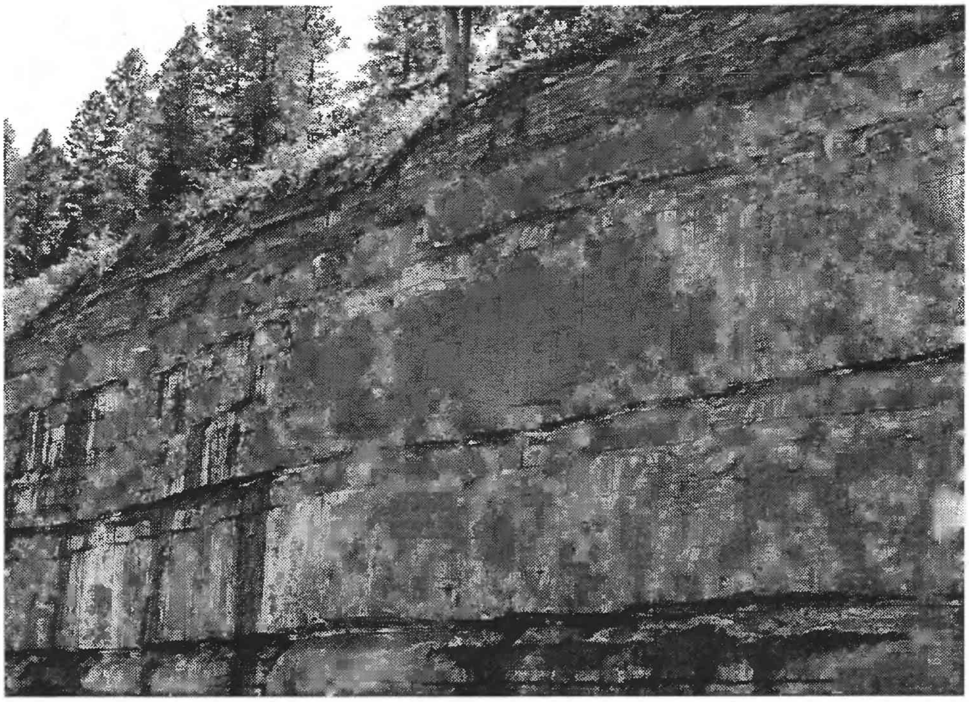


FIGURE 27.—Lower member of the Pennsylvanian Hermosa Formation north of Durango, Colo. The lower member here consists of massively bedded limestone with thin shale interbeds. Dark streaks on the cliff face are seeps of water emanating from the shale intervals.

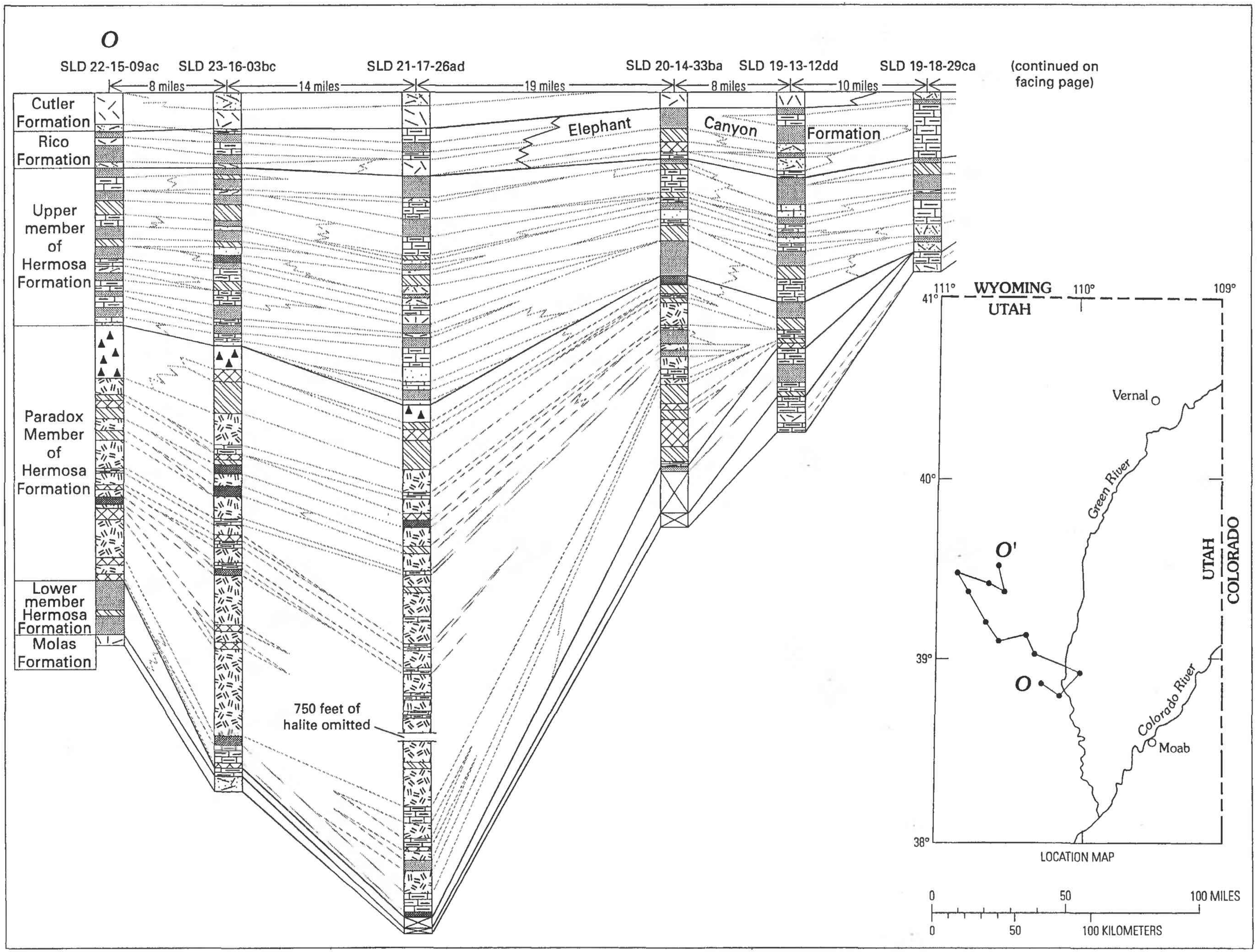
92–206 ft thick in the eastern Grand Canyon and Marble Canyon (McKee, 1982, p. 41).

### CONTACTS

Although the base of the Belden-Molas subunit is a pronounced unconformity over most of the region, contacts between geologic units within the Belden-Molas subunit and contacts with formations in overlying hydrogeologic units generally are conformable. For example, the Horseshoe Shale Member of the Amsden Formation grades laterally into the Moffat Trail Limestone Member or is overlain conformably by the Ranchester Limestone Member of the Amsden Formation (Sando and others, 1975, p. 24). Contacts between the Doughnut Shale and the Pennsylvanian Round Valley Limestone are poorly exposed; where visible, they are conformable (Huddle and others, 1951; Kinney, 1955, p. 37; Baker and Crittenden, 1961; Hansen, 1965b, p. 43). The Molas Formation is overlain unconformably by the Belden Formation (De Voto, 1980b, p. 77) but grades into the lower member of the Hermosa Formation (Merrill and Winar, 1961, p. 86). The Belden Formation grades into the Gothic Formation (of Langenheim, 1952), Minturn Formation, and Eagle Valley Evaporite of Pennsylvanian age (see Tweto and Lovering, 1977, p. 35; Bryant, 1979, p. 25). The lower member of the Hermosa Formation is overlain conformably or gradationally by the Paradox and upper members of the Hermosa Formation; locally, this contact is a disconformity beneath channel sandstone, carbonaceous shale, and coal (Wengerd, 1958, p. 118). The Surprise Canyon Formation is overlain unconformably by the Watahomigi Formation (Billingsley and Beus, 1985, p. 27). The Watahomigi Formation contains a depositional hiatus between Morrowan and Atokan intervals but is overlain conformably by the Pennsylvanian Manakacha Formation of the Supai Group (McKee, 1982, p. 158).

### PARADOX–EAGLE VALLEY SUBUNIT

The Paradox–Eagle Valley subunit of the Four Corners confining unit (pl. 14) consists of sediments that accumulated during the maximum stage of the fourth Paleozoic marine advance (Kent, 1972; Mallory, 1972). Associated with carbonate rocks laid down on shallow marine shelves are bedded evaporites deposited in marginal basins restricted by shoals and the clastic debris shed from rising land masses onto coastal plains and intertidal areas. Component geologic units include the Moffat Trail Limestone Member of the Amsden Formation, the Round Valley Limestone, the Eagle Valley Evaporite, the Paradox Member of the Hermosa Formation, and the Manakacha Formation of the Supai Group (table 1 and pl. 5). On the basis of abundant paleontological evidence (mainly brachiopods, corals, and foraminifera), the sedimentary rocks comprising the Paradox–Eagle Valley subunit apparently increase in age from Late Mississippian (Chesterian) to Middle Pennsylvanian (Desmoinesian) in a south-southeasterly direction (age information from Kinney, 1955, p. 42–43; Wengerd, 1958, p. 115; Bass and Northrop, 1963, p. 43–46; Baker, 1964; Hansen, 1965b, p. 43–44; Mallory, 1971, p. 18–20; Sando and others, 1975, p. 31; McKee, 1982, p. 107; Blakey and Baars, 1987). The sea, therefore, appears to have advanced from the north and west toward the south and east at the time of deposition.


O
SLD 22-15-09ac
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SLD 19-18-29ca
(continued on facing page)
8 miles
14 miles
19 miles
8 miles
10 miles
Cutler Formation
Rico Formation
Upper member of Hermosa Formation
Paradox Member of Hermosa Formation
Lower member Hermosa Formation
Molas Formation
Elephant Canyon Formation
750 feet of halite omitted
111°
110°
109°
41°
40°
39°
38°
WYOMING
UTAH
COLORADO
Vernal
Green River
Colorado River
Moab
O'
O
LOCATION MAP
0
50
100 MILES
0
50
100 KILOMETERS

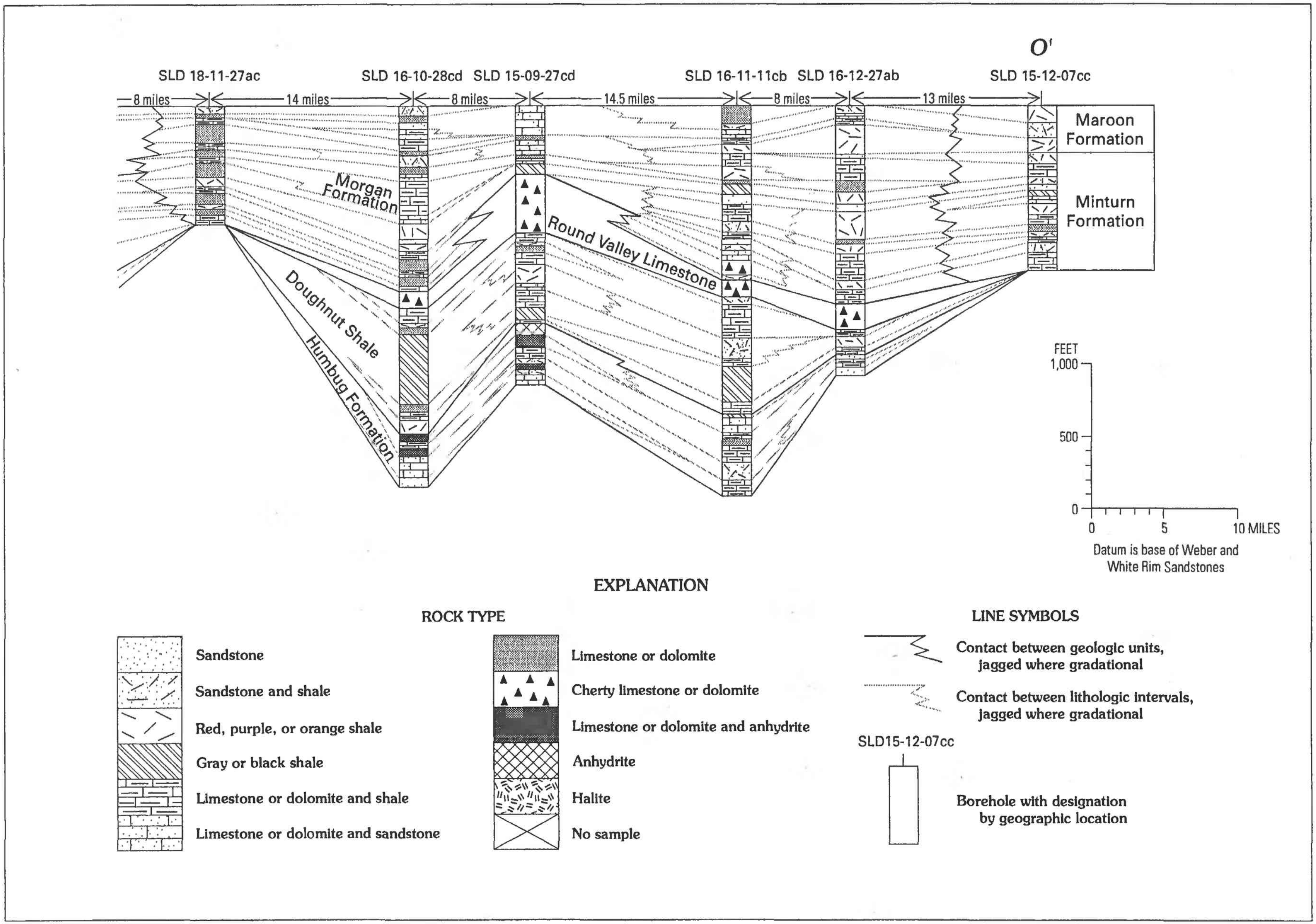



FIGURE 28.—Stratigraphic section showing relations among Pennsylvanian and Permian formations in southeastern Utah.

The thickness of the Paradox–Eagle Valley subunit increases irregularly toward the centers of the depositional basins of the component geologic units (pl. 14). Maximum thicknesses are between 300 and 400 ft in depositional basins of the Moffat Trail Limestone Member and Manakacha Formation and about 500 ft in the depositional basin of the Round Valley Limestone. Thicknesses penetrated by drilling exceed 4,000 ft in the Eagle Valley Evaporite depositional basin and 9,000 ft in the Paradox Member depositional basin, but thicknesses in these two basins are distorted by diapiric intrusion of halite and anhydrite (Hite and Lohman, 1973, p. 28; this report, fig. 5). Because of lateral and vertical gradation into other formations, nondeposition over ancestral uplifts, and erosion, the Paradox–Eagle Valley subunit is thin or absent in four areas: (1) A northwesterly trending belt extending from the Front Range of Colorado to the Green River Basin of Wyoming; (2) the Uinta Mountains and Axial Basin Arch; (3) a northwesterly trending belt extending from the Sawatch Range and southern Elk Mountains in Colorado to the Uncompahgre Plateau and southwestern Uinta Basin in Utah; and (4) a northerly trending belt extending from the Kaibito and Kaiparowits Basins in the vicinity of the Utah-Arizona State line to the San Rafael Swell and Wasatch Plateau in southeastern Utah.

## COMPONENT GEOLOGIC UNITS

The Moffat Trail Limestone Member of the Amsden Formation comprises the Paradox–Eagle Valley subunit in the Wind River Mountains, Gros Ventre Range, and Overthrust Belt of Wyoming. As described by Sando and others (1975, p. 30), the Moffat Trail Limestone Member primarily consists of thinly to thickly bedded, light-gray, medium- to coarse-grained, fossiliferous limestone with chert nodules and lenses. Locally, the Moffat Trail Limestone Member contains interbeds of yellowish-brown and beige dolomite or dolomitic limestone, fine-grained sandstone, or dark-gray fissile shale.

The Round Valley Limestone comprises the Paradox–Eagle Valley subunit in the greater Green River Basin, Uinta, Sand Wash, and Piceance Basins and adjacent uplifted areas (the Uinta Mountains and Wasatch Range). In the eastern Uinta Mountains, the Round Valley Limestone (fig. 4) consists of thinly to massively bedded, light-gray, fine- to coarse-grained, cherty limestone (Kinney, 1955, p. 40–41; Hansen, 1965b, p. 43). In the Duchesne River area of the western Uinta Mountains, the Round Valley Limestone consists of gray, white, and brown, cherty, fine-grained, oolitic, shaly and sandy limestone with interbedded limy sandstone (Huddle and McCann, 1947a). Similarly, in the Wasatch Range and western Uinta Basin, the Round Valley Limestone consists of light- to medium-gray, moderately to coarsely crystalline, cherty limestone with some thin beds of buff and gray sandstone (Baker, 1964). In the southeastern Uinta Basin, the Round Valley Limestone in boreholes consists of buff, gray, and brown cherty limestone with oolitic and sandy layers and some interbeds of white, gray, and buff sandstone and greenish-gray, light-gray, black, and red shale.

The Round Valley Limestone grades into the Eagle Valley Evaporite in northwestern Colorado east of the Douglas Creek Arch and south of the Sand Wash Basin (fig. 24). The Eagle Valley Evaporite (fig. 29) consists of evaporites, carbonate rocks, and clastic rocks that can be grouped into at least 10 depositional cycles exhibiting lateral facies changes from hypersaline to penesaline to marine-shelf lithologies (De Voto

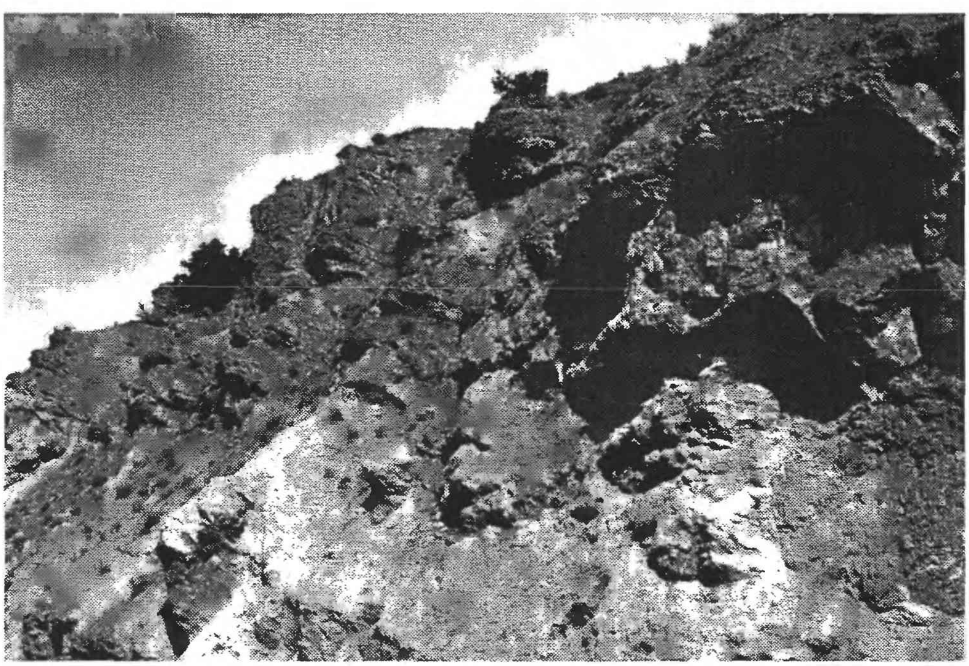


FIGURE 29.—Bedded gypsum and gypsiferous mudstone overlain by sandstone in the Pennsylvanian Eagle Valley Evaporite near Eagle, Colo.

and others, 1986, p. 42–43; Dodge and Bartleson, 1986, p. 114–118). The hypersaline facies, consisting of massively bedded halite with thin interbeds of black shale, anhydrite, and carbonate rocks, was deposited in five areas that were actively subsiding grabens at the time of deposition (fig. 30). Peripheral to these areas, the penesaline facies was deposited in shallow seas, as evidenced by stromatolites, mud cracks, and raindrop imprints (Dodge and Bartleson, 1986, p. 118). The penesaline facies consists of black, gray, white, and tan siltstone, mudstone, and anhydrite (or gypsum) with minor interbeds of limestone, dolomite, sandstone, and conglomerate (see description at Dotsero, Colo., by Bass and Northrop, 1963, p. 42–43). Near the eastern and western depositional limits of the Eagle Valley Evaporite, where the formation grades into the Minturn and Gothic Formations, the penesaline and hypersaline facies contain numerous interbeds of red, maroon, tan, and gray arkosic conglomerate, grit, sandstone, siltstone, mudstone, limestone, and dolomite (Mallory, 1971, pl. 2). At its northern depositional limits, where the Eagle Valley Evaporite grades into the Round Valley Limestone, the marine shelf facies of the Eagle Valley Evaporite consists of thickly bedded limestone and thinly bedded black shale, with some conglomeratic sandstone and minor anhydrite (less than 5 percent of the formation). Mounds of algal limestone, dolomitized toward depositional centers, are present in both the marine shelf and penesaline facies.

Analogous to the Eagle Valley Evaporite and Round Valley Limestone south of the Uinta Basin and Uncompahgre Plateau, the Paradox Member of the Hermosa Formation also consists of a hypersaline facies grading outward to penesaline and marine shelf facies. However, the Paradox Member contains fewer sandstone intervals and thicker, more laterally extensive deposits of halite (see Dodge and Bartleson, 1986, p. 116, for a comparison of lithofacies distributions in the two geologic units). Like the Eagle Valley Evaporite and its equivalents, thickness and depositional limits of the Paradox Member cannot be established precisely because of vertical and lateral gradation into other geologic units. (Several, but not all, classification schemes commonly used for rocks in the Paradox Member are listed in table 2.) For this report, the top of the Paradox Member (fig. 31) generally was placed at the top of a thick interval of cherty limestone and dolomite underlain by interbedded anhydrite, dark-gray to black mudstone, tan, gray-brown, and gray siltstone, and limestone or dolomite and overlain by interbedded sandstone, shale, and carbonate rocks typical of the upper member of the Hermosa Formation (fig. 28). In some areas, particularly in the eastern Paradox Basin or adjacent to the Uncompahgre Uplift, where the capping layer of cherty limestone and dolomite is not present, the top of the Paradox Member was placed at the top of the distinctive rocks that normally underlie the carbonate interval. The bottom of the Paradox Member generally was placed at the base of the lowest anhydrite interval, although toward the margins of deposition, the base of the Paradox Member was interpreted in some boreholes to be either a thick interval of cherty or anhydritic dolomite, dark-gray and black anhydritic mudstone, tan siltstone, or light-colored, locally cherty or anhydritic sandstone.

The Paradox Member of the Hermosa Formation consists of chemical, biogenic, and clastic sediments that accumulated during 29 cycles of sea level fluctuation in a barred trough adjacent to the ancestral Uncompahgre Uplift (Hite and Cater, 1972; Hite and Lohman, 1973). In the largest part of this trough, an area of more than 11,000 mi$^2$ south of the present-day Uncompahgre Plateau, the Paradox Member consists of an evaporite facies, predominantly composed of halite. A typical evaporite cycle of rising and falling salinity in ascending order consists of (1) black, calcareous, silty, carbonaceous shale, (2) black and gray silty dolomite, (3) gray and white nodular and laminated anhydrite, (4) gray, red, and tan halite with potash salts (mainly sylvite and carnallite) and anhydrite laminae, (5) anhydrite, (6) silty dolomite, and (7) black shale. The top of the halite interval is a disconformity produced by removal of 5–10 ft of salt between regressive and transgressive phases. Typically, the black shale layers are repeated at intervals of 100–300 ft (Hite and Lohman, 1973, figs. 6 and 7; Baars, 1983, p. 70).

In the deep northeastern part of the Paradox Basin, an area of about 3,000 mi$^2$, the salt has been squeezed into five systems of northwest-trending diapiric anticlines (Cater, 1970); bedding in the cores of these structures is disrupted severely. In the center of these anticlines, salt comprises 70–80 percent of the Paradox Member, which is interpreted to be 2,500–15,000 ft thick (see, for example, fig. 5). At the crest of the anticlines is an interval of brecciated caprock that formed by dissolution of salt layers in the Paradox Member and collapse of overlying sedimentary rocks. In Salt Valley, Utah, the caprock is 500–1,000 ft thick and consists of gypsum, siltstone, claystone, and subordinate black shale, dolomite, limestone, and sandstone (Wollitz and others, 1982). In Moab Valley, Utah, jumbled masses of gypsum, black shale, and dolomite, 800 ft thick, form the caprock (Baars and Doelling, 1987, p. 276). Migration of salt into the anticlines thinned or removed salt from adjacent synclines. For example, salt flowage into the Paradox Valley and Gypsum Valley Anticlines completely removed salt from the intervening Dry Creek Syncline. Salt thicknesses can vary from 0 to more than 10,000 ft within a horizontal distance of less than 3 mi (Hite and Lohman, 1973, p. 15) because of salt flowage.

On the southwestern edge of the Paradox Basin, carbonate sediments accumulated under relatively shallow marine conditions. Evaporite cycles are traceable into the carbonate sequence (Hite and Cater, 1972, p. 136). A typical carbonate cycle, in an order parallel to the evaporite cycle, consists of (1) black calcareous shale, (2) silty dolomite and limestone, (3) algal limestone, (4) pelletal and foraminiferal limestone, (5) siltstone, sandstone, or very silty dolomite, and (6) black shale. The disconformity corresponding to the top of the halite in the evaporite cycle occurs at the top of the pelletal and foraminiferal limestone.

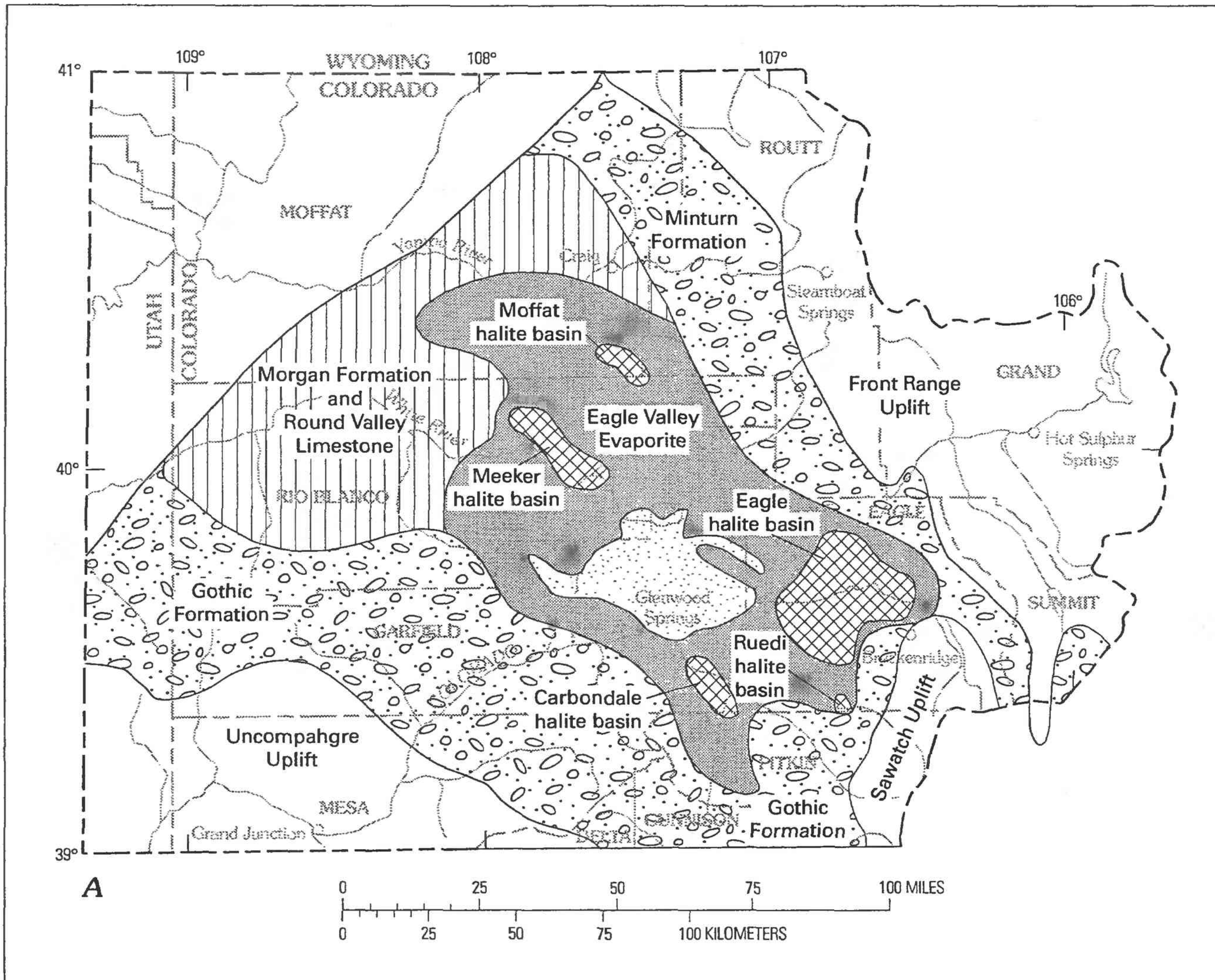


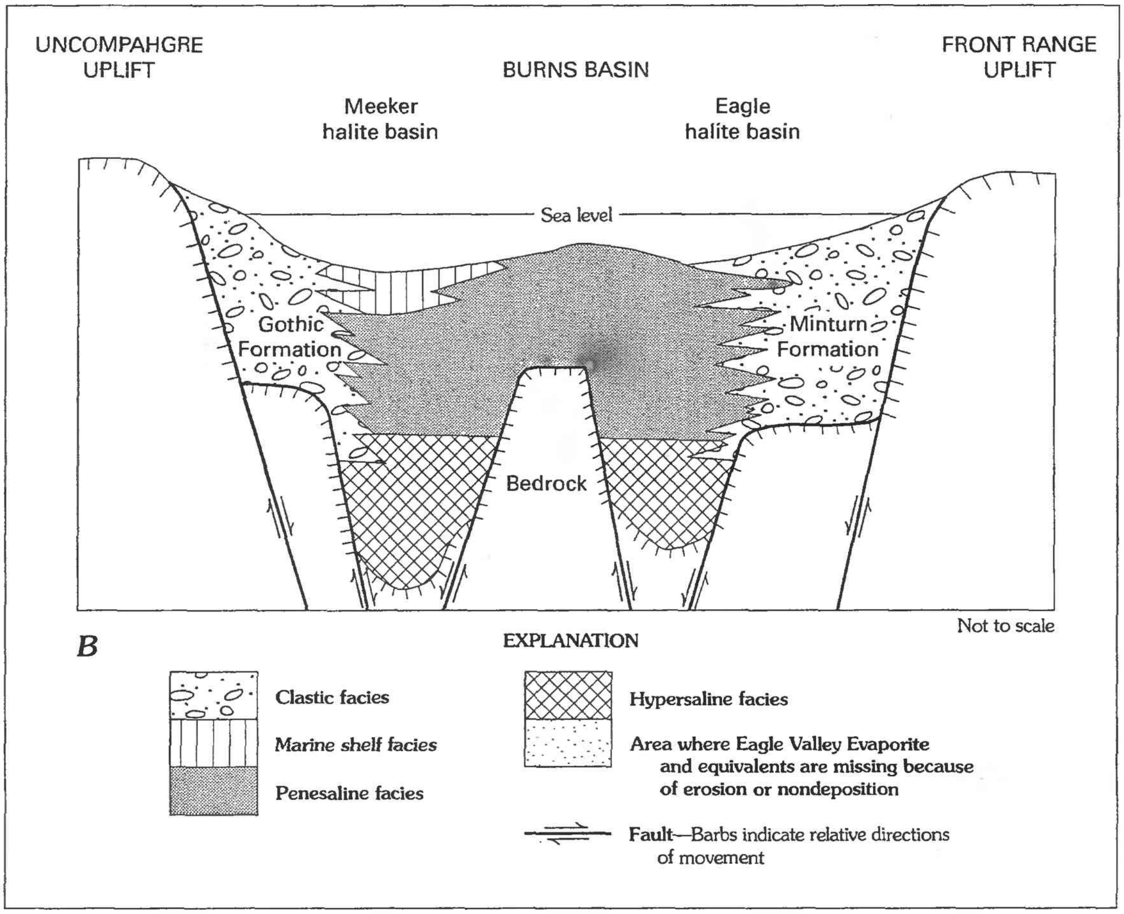

FIGURE 30 (above and facing page).—Map and schematic section showing distribution of depositional facies in the Eagle Valley Evaporite and contemporaneous Pennsylvanian formations, northwestern Colorado. *A*, Map showing depositional facies in the Eagle Valley Evaporite, laterally equivalent geologic formations, and syndepositional uplifts. Modified from Dodge and Bartleson (1986, fig. 6). *B*, Schematic section showing relation of depositional facies in the Eagle Valley Evaporite and equivalents to tectonic setting. Based on De Voto and others (1986, fig. 3); Dodge and Bartleson (1986, fig. 7).

On the northeastern edge of the Paradox Basin, where the Paradox Member grades into the upper and lower members of the Hermosa Formation, clastic sedimentary rocks derived from erosion of the ancestral Uncompahgre Uplift interfinger with evaporite facies sediments. In this area, the Paradox Member consists of greenish-gray, micaceous to arkosic sandstone and conglomerate; green, gray, and brownish-red sandy shale; dark-gray to black carbonaceous and micaceous fossiliferous limestone and dolomite with thin beds of gypsum; and, locally, thin coal seams near the base (Eckel and others, 1949, p. 8–12; Larsen and Cross, 1956, p. 46; Wengerd, 1957, p. 133–135; McKnight, 1974, p. 19–20, 23–26).

In the vicinity of the Kaibab Plateau and Marble Platform, the Paradox Member grades into the Manakacha Formation of the Supai Group (fig. 2). The Manakacha Formation consists of a lower cliff-forming unit and an upper slope-forming unit. The lower unit consists of orange-pink, reddish-brown, and red, very fine grained to medium-grained sandstone and siltstone and gray, red, and orange limestone with thin layers of jasper. The upper unit consists of reddish-brown, orange, and red siltstone, mudstone, and very fine grained sandstone with nodules and sparse interbeds of fine-grained limestone (McKee, 1982, p. 40, 391–399).

UPPER CONTACTS

Contacts between formations comprising the Paradox–Eagle Valley subunit and overlying formations are disconformable to gradational. The Moffat Trail Limestone Member of the Amsden Formation is overlain conformably by the Ranchester



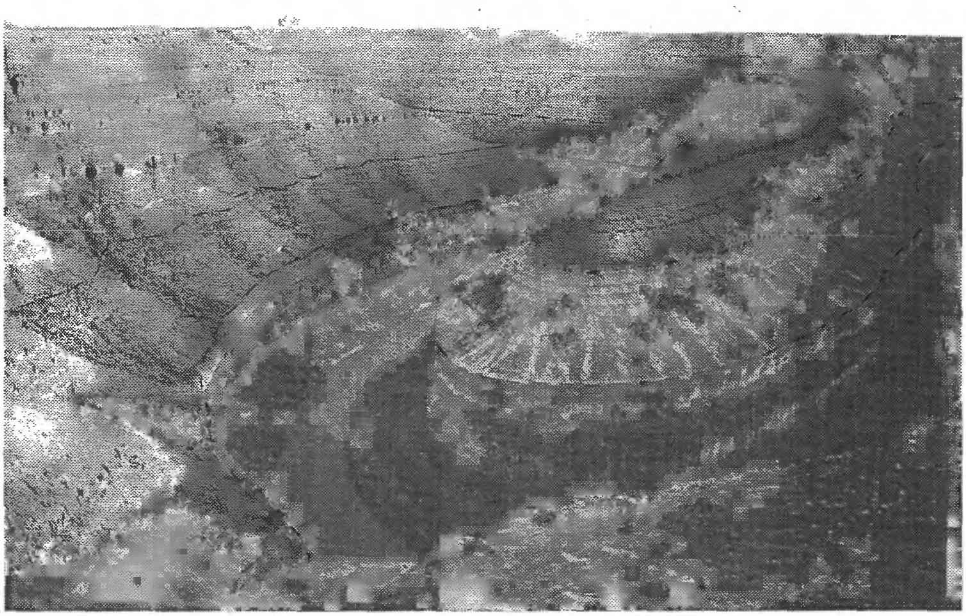



FIGURE 31.—Pennsylvanian Hermosa Formation exposed in the Goosenecks of the San Juan River west of Mexican Hat, Utah. The band delineated in the center of the picture is cherty limestone of the Ismay cycle, which generally is considered to be the top of the Paradox Member.

TABLE 2.—*Stratigraphic nomenclature for the Pennsylvanian System in the Paradox Basin.*

<table>
<tr><th colspan="2" rowspan="2">U.S. GEOLOGICAL SURVEY</th><th colspan="2" rowspan="2">WENGERD (1957)</th><th colspan="2" rowspan="2">WENGERD (1958)</th><th colspan="3" rowspan="2">PETERSON AND OHLEN (1963)</th><th colspan="11">BAARS AND OTHERS (1960)</th><th rowspan="2">GENERAL LITHOLOGY</th></tr>
<tr><th colspan="4">TEXACO</th><th colspan="2">SUN</th><th colspan="2">UNION</th><th colspan="3">SHELL</th></tr>
<tr><td rowspan="8">Hermosa Formation</td><td>Upper member</td><td rowspan="8">Hermosa Group</td><td>Hermosa Formation</td><td rowspan="8">Hermosa Group</td><td>Honaker Trail Formation</td><td rowspan="8">Hermosa Group</td><td colspan="2">Honaker Trail Formation</td><td rowspan="8">Hermosa Group</td><td colspan="3">Honaker Trail Formation</td><td colspan="2">Hermosa Formation</td><td rowspan="4">Hermosa Formation</td><td></td><td rowspan="8">Hermosa Formation</td><td rowspan="3">Upper member</td><td></td><td>Sandstone, shale, and limestone</td></tr>
<tr><td rowspan="6">Paradox Member</td><td rowspan="6">Paradox Formation</td><td rowspan="6">Paradox Formation</td><td rowspan="6">Paradox Formation</td><td rowspan="2">Ismay cycle</td><td rowspan="6">Paradox Formation</td><td rowspan="3">Upper member</td><td rowspan="2">Ismay zone</td><td rowspan="7">Paradox Formation</td><td rowspan="2">Ismay zone</td><td>Bluff zone</td><td rowspan="2">Bluff zone</td><td rowspan="2">Limestone with shale layers</td></tr>
<tr><td>Ismay zone</td></tr>
<tr><td>Desert Creek cycle</td><td>Desert Creek zone</td><td>Desert Creek zone</td><td>Desert Creek zone</td><td rowspan="4">Paradox Member</td><td>Desert Creek zone</td><td>Limestone, salt, or anhydrite</td></tr>
<tr><td>Akah cycle</td><td>Middle member</td><td>Akah zone</td><td rowspan="2">Paradox Salt zone</td><td colspan="2" rowspan="2">Paradox Formation</td><td>Akah zone</td><td rowspan="2">Salt with shale, anhydrite, or dolomite layers</td></tr>
<tr><td>Barker Creek cycle</td><td rowspan="2">Lower member</td><td>Barker Creek zone</td><td rowspan="2"></td></tr>
<tr><td>Alkali Gulch cycle</td><td>Lower Paradox zone</td><td rowspan="2">Lower Paradox zone</td><td colspan="2" rowspan="2">Pinkerton Trail Formation</td><td>Shale, dolomite, and anhydrite</td></tr>
<tr><td>Lower member</td><td>Pinkerton Trail Formation</td><td>Pinkerton Trail Formation</td><td colspan="2">Pinkerton Trail Formation</td><td colspan="3">Pinkerton Trail Formation</td><td colspan="2">Lower member</td><td>Limestone and shale</td></tr>
<tr><td colspan="2">Molas Formation</td><td colspan="2">Molas Formation</td><td colspan="2">Molas Formation</td><td colspan="3">Molas Formation</td><td colspan="4">Molas Formation</td><td colspan="2">Molas Formation</td><td colspan="2">Molas Formation</td><td colspan="3">Molas Formation</td><td>Red shale with limestone fragments</td></tr>
</table>

Limestone Member of the Amsden Formation (Sando and others, 1975, p. 30). The Round Valley Limestone in the Wasatch Range and western Uinta Basin appears to be overlain conformably by the Weber Sandstone of Pennsylvanian age (Baker, 1964), but in the Uinta Mountains, the Round Valley Limestone is overlain disconformably to gradationally by the Morgan Formation of Pennsylvanian age (Huddle and McCann, 1947b; Kinney, 1955, p. 44; Ritzma, 1959, p. 26). The Eagle Valley Evaporite grades laterally into the Minturn and Gothic Formations and the lower part of the Morgan Formation and is overlain conformably by the upper part of the Morgan Formation and the Maroon Formation (Mallory, 1971, p. 14–18 and pl. 2); all formations in contact with the Eagle Valley Evaporite are Pennsylvanian in age. The Paradox Member of the Hermosa Formation is overlain gradationally by the upper member of the Hermosa Formation (Baars, 1983, p. 69). The Manakacha Formation is separated from the overlying Wescogame Formation of Pennsylvanian age by a widespread erosional surface characterized by many small to moderately deep channels (McKee, 1982, p. 40).

## PALEOZOIC ROCKS OF THE STRAWBERRY VALLEY AREA

Some Paleozoic rocks that crop out in the Strawberry Valley area of the UCRB occur nowhere else in the UCRB. They are present in the Strawberry Valley area only because cumulative movement on the Charleston Thrust Fault and other thrust faults have displaced rocks normally found many miles to the west in the Basin and Range physiographic province (Roberts and others, 1965). As shown in figure 32, the typical Mississippian to Permian sequence present east of the Strawberry Valley area in the Uinta Basin and Uinta Mountains underlies the Mississippian to Permian rocks above the Charleston Thrust Fault and presumably transmits water into the UCRB from areas north of the fault where the autochthonous rocks crop out (Baker, 1964). Consequently, the allochthonous rocks are not included in any of the UCRB hydrogeologic units. However, because of their geologic importance, the allochthonous rocks are described briefly in this section.

The oldest Paleozoic geologic unit found above the Charleston Thrust Fault but not below it is the Great Blue Limestone of Late Mississippian age. According to Baker (1972), the Great Blue Limestone characteristically consists of 2,800 ft of very thinly bedded, dark-gray to black, cherty limestone with intervals of black shale as much as 50 ft thick and, near the bottom, thin interbeds of olive-brown-weathering quartzite. Conformably overlying the Great Blue Limestone is the Manning Canyon Shale of Late Mississippian and Early Pennsylvanian age. The Manning Canyon Shale consists of 1,650–1,800 ft of brown to black shale with numerous thin interbeds of brown to reddish-brown-weathering quartzite and pebbly sandstone and thinly to thickly bedded, gray to black, cherty limestone (Baker, 1972). The Oquirrh Formation conformably overlies the Manning Canyon Shale.

The Oquirrh Formation consists of five members and is about 25,000 ft thick in the Charleston thrust sheet (Baker, 1976). The lowermost member, the Bridal Veil Limestone Member, is Lower to Middle Pennsylvanian and approximately equivalent to the Round Valley Limestone (Baker, 1964). It consists of 1,250 ft of thinly to thickly bedded, medium- to dark-gray limestone with some interbedded dark-gray to black shale. The overlying Bear Canyon Member, of Middle Pennsylvanian age, consists of 4,000–8,350 ft of gray to tan, limy to quartzitic sandstone with numerous thin to thick beds of gray to black, sandy and cherty limestone. Next in succession, the Middle Pennsylvanian Shingle Mill Limestone Member consists of 250–500 ft of thinly bedded, dark-gray, cherty limestone. Above the limestone, the Upper Pennsylvanian Wallsburg Ridge Member consists of about 7,900 ft of light-gray to red, fine- to medium-grained quartzite with some interbedded platy, light-gray, limy sandstone and gray to blue-gray, cherty limestone. The uppermost member of the Oquirrh Formation, the Lower Permian Granger Mountain Member, consists of 5,000–7,300 ft of gray to tan, limy, silty sandstone with some interbedded gray, red, and buff quartzite, light-gray sandstone, and thin to thick beds of gray limestone.

The uppermost Paleozoic geologic units present above, but not below, the Charleston Thrust Fault are the Kirkman Limestone and Diamond Creek Sandstone, both of which are Lower Permian (Baker, 1976). The Kirkman Limestone, which unconformably overlies the Oquirrh Formation, consists of 0–1,600 ft of gray and black laminated, locally phosphatic limestone and sandy limestone with some interbedded gray, buff, and red, medium-grained sandstone and a basal boulder-conglomerate. The overlying Diamond Creek Sandstone consists of 165–1,000 ft of thinly to massively bedded, white, light-gray, buff, and red, medium- to coarse-grained, limy to quartzitic sandstone with a few thin beds of silty sandstone, red to gray, sandy limestone, and gray and black laminated limestone.

The Park City Formation, which in this area, consists of the Grandeur Member, Meade Peak Phosphatic Shale Tongue of the Phosphoria Formation, and Franson Member (Baker, 1976), is present above and below the Charleston Thrust Fault. However, the fault has brought a greatly thickened sequence of these rocks into the UCRB (Bissel, 1952; Baker, 1964, unpublished AMSTRAT drilling logs). Thicknesses of the Park City Formation in measured sections and a borehole above the fault (at SLD 03-05-16dcb) range from about 1,430 to 1,900 ft. In contrast, the Park City Formation in an outcrop north of the fault and in a borehole through the fault (at SLD 05-05-11bb) ranges from 624 to 870 ft thick (Baker, 1964; Bruce Bryant, U.S. Geological Survey, oral commun., 1990).

Only the uppermost strata of the allochthonous sequence extend into the Strawberry Valley area. Bissell (1952) mapped about 11,100 ft of the Oquirrh Formation on the west side of Strawberry Valley. From the ages given by Bissell (1952),

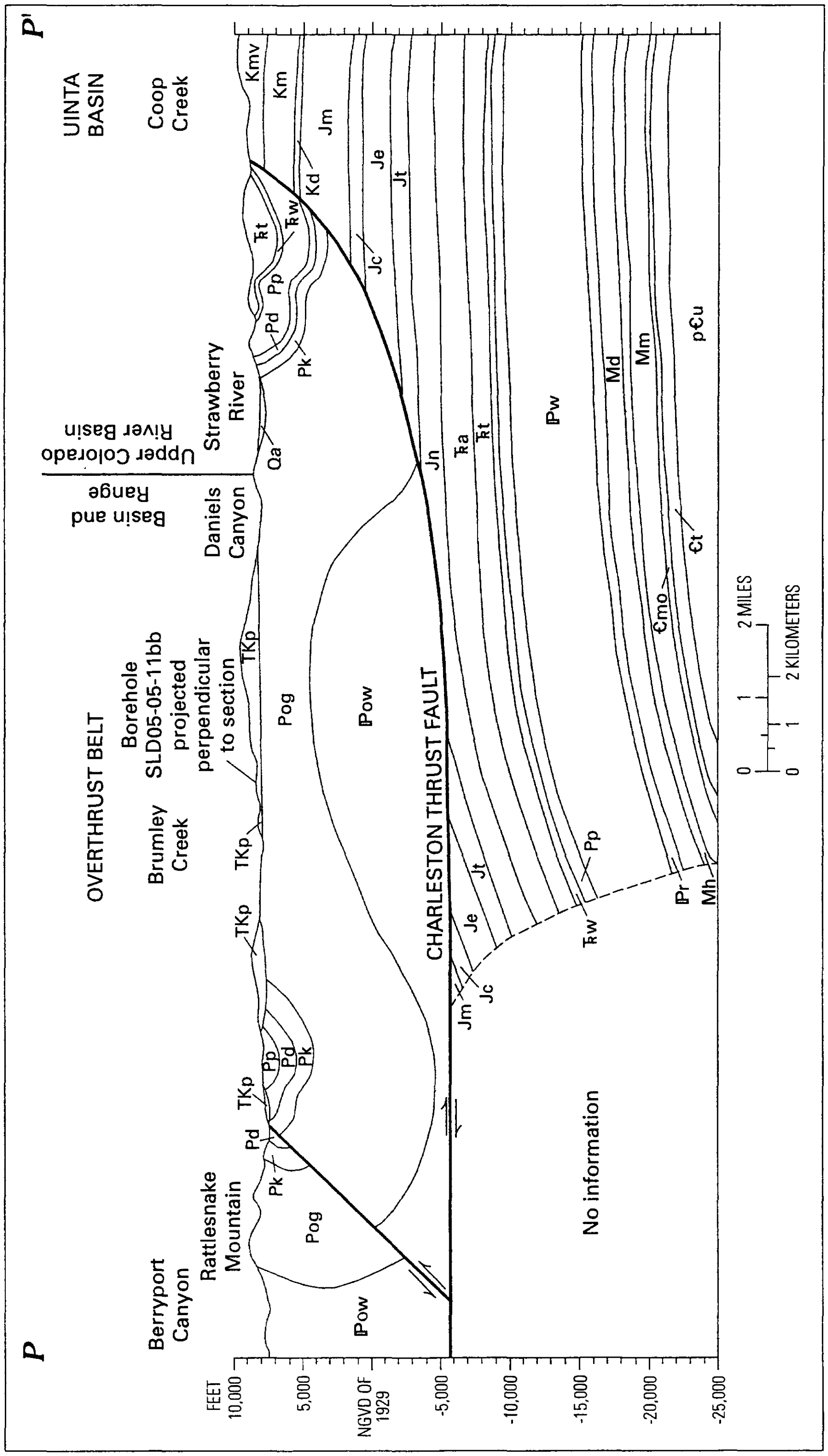



FIGURE 32 (above and facing page).—Geologic section showing stratigraphy and structure in Strawberry Valley area, Utah. Modified from section *B–B′* of Baker (1976), using information from Bissell (1952) and unpublished data from borehole SLD 05-05-11bb provided by Bruce Bryant (U.S. Geological Survey, oral commun., 1990). Section should be considered generalized because of sparse subsurface information and problems in reconciling geologic maps by Baker (1976) and Bissell (1952).

these strata apparently represent the upper part of the Wallsburg Ridge Member and the entire Granger Mountain Member. In the same area, Bissell (1952) mapped the Kirkman Limestone as 875 ft thick, the Diamond Creek Sandstone as 165 ft thick, and the Park City Formation as 1,495 ft thick.

## CANYONLANDS AQUIFER

Rocks equivalent to the C multiple-aquifer of the Navajo and Hopi Indian Reservations in Arizona, New Mexico, and Utah (Cooley and others, 1969) extend throughout the UCRB. The

## EXPLANATION

| | |
|---|---|
| Qa | Alluvium |
| TKp | Price River Formation |
| Kmv | Mesaverde Formation |
| Km | Mancos Shale and Mowry Formation |
| Kd | Dakota Sandstone |
| Jm | Morrison Formation |
| Jc | Curtis Formation |
| Je | Entrada Sandstone |
| Jt | Twin Creek Limestone |
| Jn | Nugget Sandstone |
| TRa | Ankareh Formation |
| TRt | Thaynes Formation |
| TRw | Woodside Shale |

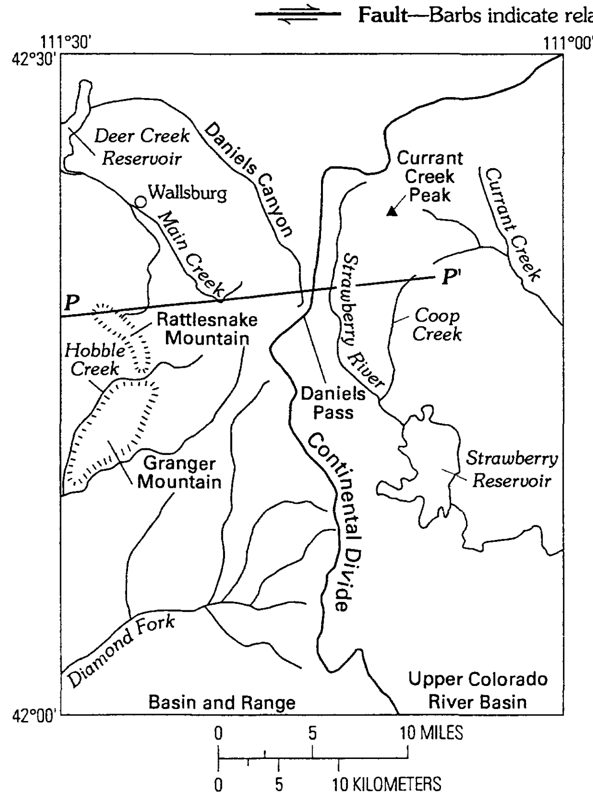
Pennsylvanian and Permian rocks above thrust fault

| | |
|---|---|
| Pp | Park City Formation |
| Pd | Diamond Creek Sandstone |
| Pk | Kirkman Limestone |
| Pog | Oquirrh Formation, Granger Mountain Member |
| ₱ow | Oquirrh Formation, Wallsburg Ridge Member |

Pennsylvanian and Permian rocks below thrust fault

| | |
|---|---|
| Pp | Park City Formation |
| ₱w | Weber Sandstone |
| ₱r | Round Valley Limestone |
| Md | Doughnut Shale |
| Mh | Humbug Formation |
| Mm | Madison Limestone and equivalents |
| €mo | Maxfield Limestone and Ophir Shale |
| €t | Tintic Quartzite |
| p€u | Precambrian rocks |

Fault—Barbs indicate relative movement



C multiple-aquifer extends from the upper part of the Supai Group to the Kaibab Limestone and, thus, includes all Paleozoic rocks above the Four Corners confining unit. To be consistent with current practice of the U.S. Geological Survey for naming hydrogeologic units (Laney and Davidson, 1986), the C multiple-aquifer herein is named the Canyonlands aquifer because of its importance as a source of water in the Canyonlands region of Utah, as well as in other deeply dissected areas of the UCRB.

The Canyonlands aquifer vertically is divisible into three zones with different lithologic and hydrologic properties. The lowermost zone, the Cutler-Maroon zone, consists mostly of interbedded clastic and carbonate rocks and is named after the two geologic units within the zone most characteristic of its lithology and most often used as sources of water. The middle zone, the Weber–De Chelly zone, consists almost entirely of quartz sandstone and is named for the two most prominent water-bearing formations within this zone. The uppermost zone, the Park City–State Bridge zone, consists alternately of carbonate rocks, carbonate and clastic rocks, or shale, and is named for the two geologic units most representative of the extensive regional variations in lithology within the uppermost zone.

Depths to the top of the Canyonlands aquifer generally coincide with depths to the top of the Paleozoic rocks shown on plate 3. The aquifer is at or near land surface on the flanks of the White River, Uncompahgre, Defiance, and Kaibab Plateaus, the Sawatch and Gore Ranges, and the Uinta, Elk, and San Juan Mountains and has considerable exposure in the San Rafael Swell, Waterpocket Fold (Capitol Reef–Circle Cliffs area), Monument Upwarp, Overthrust Belt, Eagle Basin, and Paradox Basin. The aquifer is less than 5,000 ft deep in most areas south of the Uncompahgre Plateau, although it is more than 10,000 ft deep in the High Plateaus region. Widespread areas exist north of the Uncompahgre Plateau—the Uinta, Piceance, Sand Wash, and greater Green River Basins—where the aquifer is 15,000 to more than 25,000 ft deep.

### CUTLER-MAROON ZONE

The Cutler-Maroon zone of the Canyonlands aquifer (pl. 15) consists of clastic, carbonate, and evaporite sediments that accumulated during the fourth Paleozoic depositional cycle at a time of intense tectonic activity (Kent, 1972; Mallory, 1972; Rascoe and Baars, 1972). In response to this activity, land masses on the east and south rose to mountainous heights, and the sea ebbed and flowed but eventually withdrew to the north and west. Arkosic sandstone and shale eroded from the rising mountains were deposited between the mountain fronts and coastal areas. Quartz sandstone accumulated in coastal dune fields and shoreline areas. Evaporites precipitated in restricted marine basins, and carbonate rocks accumulated in shallow seas. In general, the depositional pattern is characterized by abrupt facies changes. Consequently, stratigraphic nomenclature is extremely variable across the region. Component geologic units include the Ranchester Limestone Member of the Amsden Formation, upper member of the Hermosa Formation (Honaker Trail Formation of Wengerd, 1958), Rico Formation, Gothic Formation (of Langenheim, 1952), Minturn Formation, Morgan Formation, main body of the Maroon Formation, Cutler Formation, Halgaito Shale (of Baars, 1962), Elephant Canyon Formation (of Baars, 1962), Cedar Mesa Sandstone (of Baars, 1962), Organ Rock Shale (of Baars, 1962) Supai Formation, Wescogame Formation, Esplanade Sandstone, and Hermit Shale (table 1 and pl. 5).

On the basis of sparse to locally abundant vertebrate, invertebrate, and plant remains, component geologic units are considered to be Lower Pennsylvanian (Morrowan) to Lower Permian (Leonardian). The Ranchester Limestone Member in the Gros Ventre Range, Wind River Mountains, and Rawlins area contains an Early to Middle Pennsylvanian (Morrowan to Atokan) fauna (Sando and others, 1975, p. 34). The Morgan Formation in the eastern Uinta Mountains contains a Middle Pennsylvanian (Desmoinesian) fauna (Kinney, 1955, p. 42–44; Hansen, 1965b, p. 46–50). According to Bartleson (1972), the Minturn and Gothic Formations in northwestern Colorado, on the basis of paleontological evidence, are Middle Pennsylvanian (Atokan to Desmoinesian), and the main body of the Maroon Formation, on the basis of its stratigraphic position above the Minturn and Gothic Formations and below the Permian and Triassic State Bridge Formation, is considered to be Middle Pennsylvanian to Lower Permian (Desmoinesian to Wolfcampian). Similar to the Gothic-Maroon sequence to the north, the upper member of the Hermosa Formation, Rico Formation, and component geologic units in the Cutler Formation or Cutler Group (of Baars, 1962) in southwestern Colorado and southeastern Utah are Middle Pennsylvanian (Desmoinesian) to Lower Permian (Leonardian), according to Rascoe and Baars (1972) and Blakey and Baars (1987). Component geologic units in the Supai Formation or Group and Hermit Shale in northeastern Arizona comprise an Upper Pennsylvanian to Lower Permian (Virgilian to Leonardian) sequence (Rascoe and Baars, 1972; McKee, 1982). Together, geologic units within the Cutler-Maroon zone indicate a regional south-southwesterly decrease in age accompanying the progression of depositional environments.

The Cutler-Maroon zone thickens and thins erratically (pl. 15), reflecting the distribution of syndepositional basins and uplifts, lateral gradation of component geologic units into formations that comprise other hydrogeologic units, and erosional thinning. The Ranchester Limestone Member of the Amsden Formation is relatively thin throughout its depositional area but thickens to more than 300 ft in the Overthrust Belt and to about 400 ft east of the Rawlins Uplift (toward the Hanna Basin). The Morgan Formation thickens toward two depositional centers, one in the Uinta and Green River Basins and the other in the Piceance Basin. In both depositional centers, maximum thicknesses are between 1,000 and 1,500 ft. The Minturn Formation or Gothic Formation and the overlying main body of the Maroon Formation form a clastic wedge extending from the ancestral Front Range and Uncompahgre Uplifts to the Piceance and Uinta Basins. This clastic wedge generally exceeds 10,000 ft thick around the northern end of the Sawatch Range and in the Hoosier Pass area of the Gore Range and is 3,000–7,000 ft thick in most of the Elk Mountains and White River Plateau, but because of gradation into the Eagle Valley Evaporite, it abruptly thins to less than 2,000 ft in the central Eagle Basin. The upper member of the Hermosa Formation, the Rico Formation, and the Cutler Group (Formation) generally thicken from less than 1,500 ft to more than 10,000 ft toward the northern edge of the Paradox Basin, although some thinning occurs over the Monument Upwarp. The Supai Group (Formation) and Hermit Shale generally thicken northwesterly, increasing from less than 600 ft thick in the Defiance Plateau and eastern Grand Canyon to more than 1,500 ft thick in the Lees Ferry area and Kaiparowits Basin.

Geologic units that comprise the Cutler-Maroon zone are missing because of erosion in the center of the White River Plateau, Sawatch Range, Park Range, Gore Range, San Juan Mountains, and Uinta Mountains and probably were never deposited in a large area extending northwestward from the Front Range to the southern Wind River Mountains and northern Green River Basin, on and adjacent to the Uncompahgre Plateau, and in small areas in the Wyoming part of the Overthrust Belt, the northwestern corner of the Uinta Basin, and the High Plateaus region (pl. 15).

### COMPONENT GEOLOGIC UNITS

The Ranchester Limestone Member of the Amsden Formation comprises the Cutler-Maroon zone in the Wyoming part of the Overthrust Belt, the Gros Ventre Range, the Wind River Mountains, the Great Divide Basin, and the Rawlins Uplift. The Ranchester Limestone Member consists of carbonate rocks with subordinate clastic rocks and, locally, interbeds of gypsum and anhydrite (Mallory, 1967, p. 14; Sando and others, 1975, p. 32–33). The carbonate rocks include thinly to thickly bedded, yellowish-gray, light-gray, and purple, fine-grained to coarsely crystalline dolomite and dolomitic limestone and fine- to medium-grained limestone. Chert lenses and nodules are abundant, particularly in the dolomite layers. Thinly bedded, red and green shale and thin intervals of white and pink, fine- to medium-grained quartz sandstone occur throughout the member; sandstone beds are abundant in the upper half and predominate between the Wind River Mountains and Gros Ventre Range, in parts of the Wyoming Overthrust Belt, on the northern edge of the Great Divide Basin, and in an area on and near the Rock Springs Uplift (Mallory, 1967, pls. 2, 3, and 15). Gypsum and anhydrite interbeds occur at the northern end of the Wind River Mountains (Sando and others, 1975, p. 33) and at the northern end of the Hoback Range (Wanless and others, 1955, p. 34).

In the southern Green River Basin, strata equivalent to the Ranchester Limestone Member are assigned to the Morgan Formation despite virtually no change in lithology from areas to the north and west (Mallory, 1967, fig. 4; Sando and others, 1975, pl. 7). As described by Hansen and others (1983), the Morgan Formation in the southeastern Uinta Mountains (fig. 4) is divisible into two members. The lower member consists of variegated shale and cherty, fossiliferous limestone with thin layers of sandstone. The upper member, which comprises about two-thirds of the formation, consists of thinly bedded to massively bedded, red, tan, and gray quartz sandstone with layers of red shale in the lower part and thin interbeds of gray and pink cherty limestone throughout. The two-fold division of the Morgan Formation is traceable into the northeastern Uinta Mountains, but in this area, Hansen (1965b) chose to include beds equivalent to the upper member of the Morgan Formation in the lower part of the Weber Sandstone. In this report the beds assigned by Hansen to the lower part of the Weber Sandstone are retained in the Morgan Formation to preserve stratigraphic continuity and avoid introducing substantial lithologic heterogeneity into the Weber Sandstone. The Weber Sandstone of this report, therefore, is a nearly homogeneous formation composed of light-colored, quartz sandstone.

Between the eastern and western Uinta Mountains, considerable changes occur in the Morgan Formation. On the basis of descriptions of the formation by Huddle and McCann (1947b), Huddle and others (1951), and Kinney (1955, p. 40–42), the lower and upper members apparently merge west of Dinosaur National Monument. Limestone beds in the formation pinch out westward and do not extend beyond the Lake Fork of the Duchesne River. West of the Whiterocks River, in the central Uinta Mountains, sandstone layers in the upper part of the formation become light colored and grade into the Weber Sandstone. The remaining Morgan Formation becomes predominantly reddish brown in color. In the Duchesne River area of the western Uinta Mountains, the Morgan Formation is near its depositional edge and consists almost entirely of interbedded sandstone, siltstone, and mudstone.

In the southwestern Uinta Basin, interbedded cherty limestone and dolomite, light-colored, orange, and red sandstone, and gray, tan, red, and varicolored shale occur between beds of typical Weber Sandstone and Round Valley Limestone lithologies (fig. 28). Superficially, these beds resemble the lower part of the Weber Formation at its type locality along the Weber River in the Uinta Mountains west of the UCRB and could be assigned to the Weber Sandstone (Samuel Johnson, U.S. Geological Survey, oral commun., 1990). However, in this report, distinction between the Weber Sandstone where it contains carbonate interbeds in the western UCRB and the underlying Morgan and Elephant Canyon Formations consistently was made based on the relative thickness and abundance of carbonate intervals. Tops of the Morgan and Elephant Canyon Formations were placed where carbonate intervals became more than several tens of feet thick and began to equal or

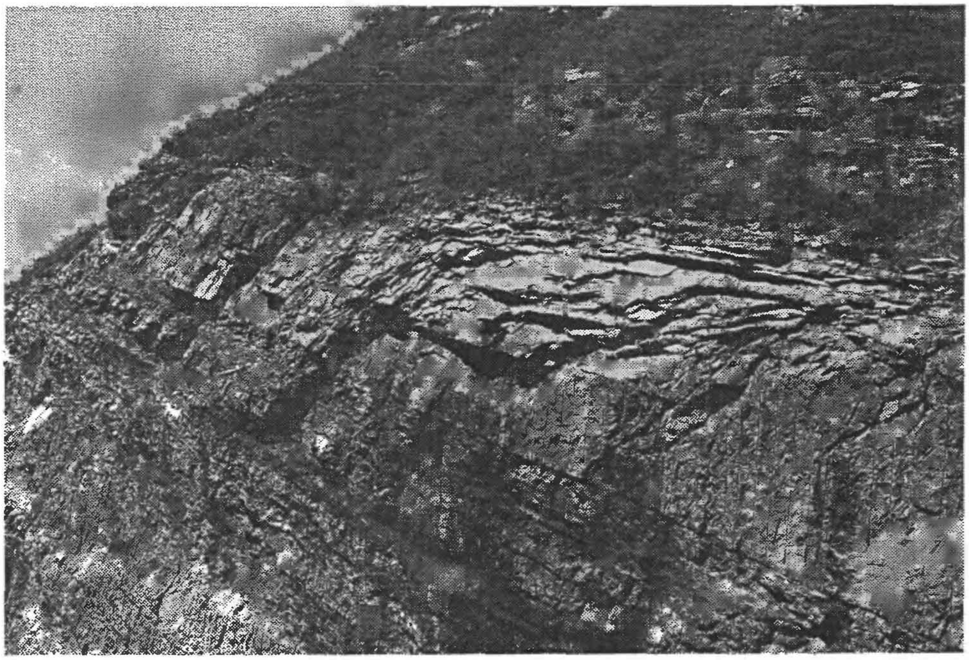


FIGURE 33.—Interbedded sandstone, shale, and dolomite in the Pennsylvanian Minturn Formation at Vail, Colo.

exceed sandstone intervals in abundance. On the basis of these criteria and their lithology, the beds in question in the southwestern Uinta Basin were assigned to the Morgan Formation.

In the eastern Eagle Basin, the lower part of the Morgan Formation and the Eagle Valley Evaporite grade into the Minturn Formation (figs. 24 and 30). The Minturn Formation (fig. 33) consists of interbedded sandstone, pebbly sandstone (grit), conglomerate, and shale with irregularly spaced intervals of limestone and dolomite and minor evaporite beds (Chronic, 1957; Boggs, 1966; Tweto and Lovering, 1977, p. 40–48). The sandstone, grit, and conglomerate commonly are arkosic, but feldspathic, graywacke, and quartz sandstone layers also are present. The arkosic rocks typically are micaceous and poorly sorted. The sandstone layers, in general, become coarser grained, thicker, and more numerous eastward as shale and evaporite layers become less abundant. Shale intervals in the Minturn Formation are gray to black; most commonly, they consist of micaceous sandy shale and siltstone, but claystone layers are present. Limestone layers in the formation are bluish gray to brownish gray and very fine grained to sandy. Dolomite layers in the formation generally are gray to black and either finely crystalline, bioclastic, or cherty. Some of the dolomite was formed by hydrothermal replacement of limestone and is gray and tan, vuggy, and coarsely crystalline. Many of the carbonate layers pinch out westward or grade laterally into clastic layers; in transition zones, mixed carbonate-clastic rocks, such as conglomerate consisting of quartz and pegmatite pebbles in a matrix of dolomite or sandy dolomite, may occur. Although most of the Minturn Formation is grayish green, tan, yellow, and pink, upper layers grade to predominantly red (see Tweto and Lovering, 1977, fig. 13). The top of the Minturn Formation is the Jacque Mountain Limestone Member (fig. 34), an interval of gray and pink limestone, about 20–25 ft thick, that in alternate layers is oolitic, sandy, bioclastic, or stromatolitic (Boggs, 1966, fig. 6).

Lithologic criteria used to distinguish the Minturn Formation from the overlying Maroon Formation in the eastern Eagle Basin and Gore Range become unusable about 7 mi west of Avon, Colo. (Boggs, 1966, p. 1403 and fig. 2). In this area, the Jacque Mountain Limestone Member becomes covered and intercalated with evaporite deposits. Although the Jacque Mountain Limestone Member may be present west of the axis of the Eagle Basin, in the White River Plateau and Elk Mountains, this particular limestone interval cannot be identified reliably among numerous other limestone intervals in the area. As an example, Langenheim (1954, p. 1768) noted that limestone intervals identified as the Jacque Mountain Limestone Member in measured sections near Glenwood Springs and Dotsero, Colo., within 20 mi of each other, were in reality separated by 1,500 feet of intervening strata. Similarly, the Jacque Mountain Limestone Member loses its identity a short distance to the south of its type locality at Minturn, Colo. De Voto (1972, p. 161) indicated that limestone beds in the Minturn-Maroon section at Hoosier Pass, 20 mi south of Minturn, cannot be correlated with confidence with limestone beds at Minturn. Because of these correlation problems, Langenheim (1952, 1954) felt that the Jacque Mountain Limestone Member was not a useful stratigraphic marker in the Elk Mountains and White River Plateau and, in these areas, rejected the Minturn Formation as a mappable unit. Instead, Langenheim established the Gothic Formation and defined its top as the change from predominantly tan, green, and gray clastic rocks to predominantly red clastic rocks. The predominantly red rocks were assigned to the Maroon Formation. Bartleson

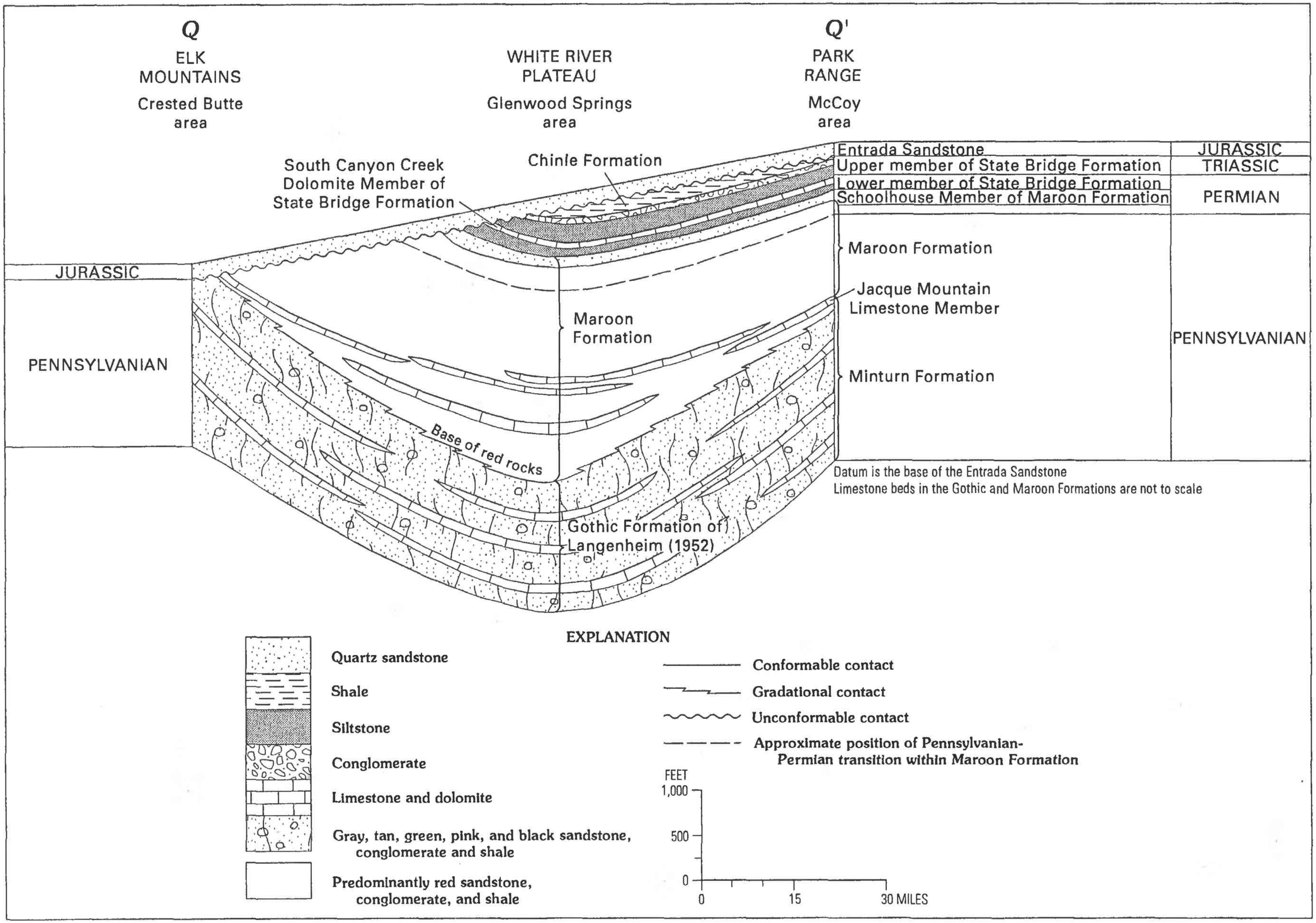



FIGURE 34.—Stratigraphic section showing relations among Pennsylvanian and Permian clastic geologic units in west-central Colorado. Compiled from reports by Brill (1944), Langenheim (1952), and Chronic (1957); location of section shown on plate 15.

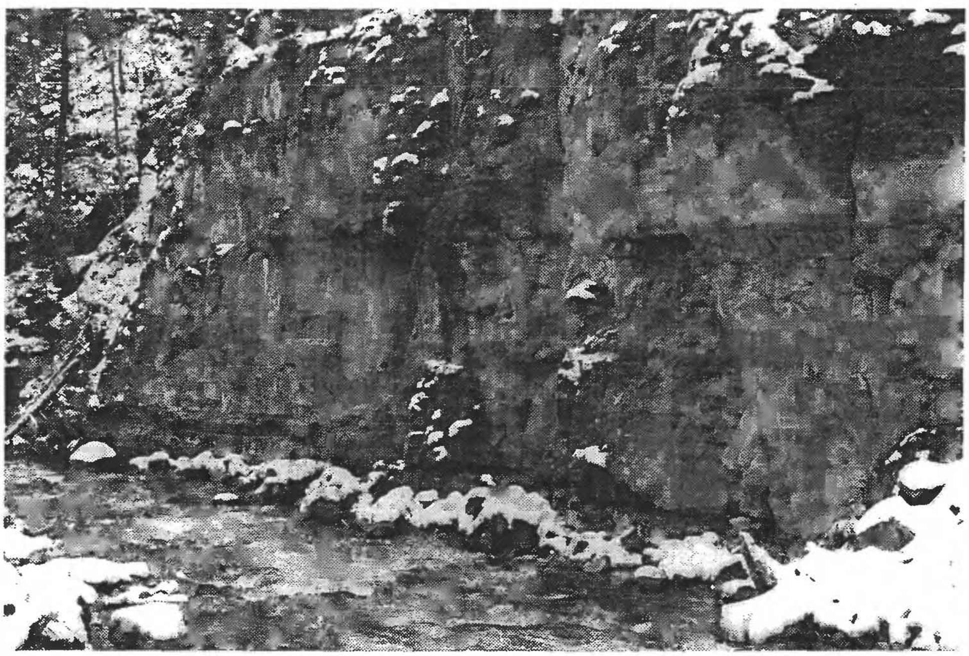


FIGURE 35.—Interbedded sandstone and conglomerate in the Pennsylvanian Gothic Formation (of Langenheim, 1952) on the Crystal River south of Carbondale, Colo.

(1972) and Bryant (1979) accepted Langenheim's terminology in subsequent reports on the Elk Mountains and Sawatch Range.

The Gothic Formation, as defined by Langenheim (1952, 1954) consists of all the predominantly light colored clastic and carbonaceous rocks between the Belden and Maroon Formations. The Gothic Formation is characterized by extreme lenticularity, with individual layers traceable for no more than 2 mi within an outcrop area and untraceable between outcrop areas. The base of the formation in the Elk Mountains and White River Plateau is the lowest prominent sandstone above shale and limestone typical of the Belden Formation. In the Sawatch Range, according to Bryant (1979, p. 25–27), the base of the Gothic Formation is gradational into the Belden Formation and consists of green, gray, and red limy shale, shaly limestone, and sandy limestone interbedded with dark-gray to black carbonaceous shale; the contact with the Belden Formation is drawn where the rocks become predominantly light colored. The upper contact of the Gothic Formation is an abrupt to gradational color change from gray, green, and tan clastic rocks to predominantly red clastic rocks. In the Elk Mountains and White River Plateau, the Gothic Formation (fig. 35) predominantly consists of siltstone with lesser amounts of sandstone and conglomerate and irregularly spaced limestone beds. The clastic rocks typically are feldspathic and locally micaceous; calcite cement may be present. The limestone layers typically are either massively bedded and sandy (grading into sandstone) or thinly bedded, organic, and shaly (with shale interbeds), but massive reef deposits also occur. In the Sawatch Range and vicinity, the Gothic Formation consists of limy sandstone and siltstone and silty to sandy limestone with interbeds of pebbly, arkosic sandstone, conglomerate, breccia, gypsum, and anhydrite (Bryant, 1979, p. 27). In general, the Gothic Formation becomes finer grained from south to north, containing more siltstone and less conglomerate and progressively finer grained sandstone layers in that direction (Langenheim, 1954, p. 1769).

Deposits that could be classified as either Gothic Formation or Minturn Formation are encountered in drill holes between the Belden Formation or Eagle Valley Evaporite and the Maroon Formation in the Piceance Basin. These deposits consist of sandstone, siltstone, and mudstone with interbeds of limestone, dolomite, and, locally, anhydrite. The top of the sequence generally is characterized by a limestone interval, 5–20 ft thick, and a color change upward from predominantly gray, white, tan, orange, grayish green, and black to predominantly red, reddish orange, reddish brown, purple, and maroon. Where a thick layer of limestone marks the top of the sequence, the color change may occur well below the limestone layer. Alternately, a thick sequence of light-colored rocks may intervene between predominantly red rocks of typical Maroon Formation lithology and the first thick limestone layer below the typical Maroon Formation beds. If the first thick limestone layer is equivalent to the Jacque Mountain Limestone Member of the Minturn Formation and rocks below it are assigned to the Minturn Formation, then the Maroon Formation uncharacteristically would include a color change in some areas of the Piceance Basin. On the other hand, if the color change is used to distinguish the Maroon Formation from the Gothic Formation, then the Maroon Formation uncharacteristically would include thick limestone intervals in some parts of the Piceance Basin. As neither system of nomenclature is satisfactory in the Piceance Basin, beds between intervals of typical Belden Formation or Eagle Valley Evaporite and Maroon Formation lithologies in this report are designated as undifferentiated Minturn-Gothic Formation.

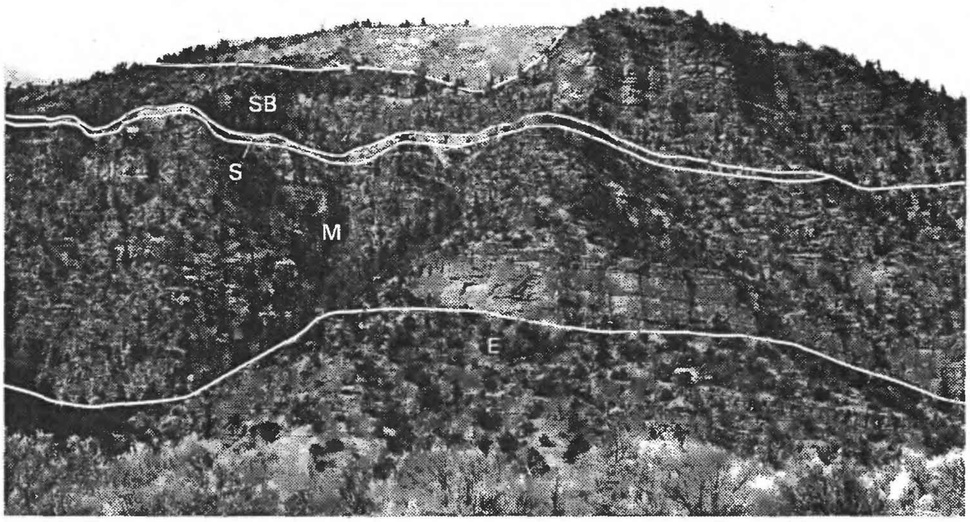



FIGURE 36.—Pennsylvanian, Permian, and Triassic formations in the Eagle River valley near Eagle, Colo. E, Eagle Valley Evaporite; M, main body of Maroon Formation; S, Schoolhouse Member of Maroon Formation; SB, State Bridge Formation. The main body of the Maroon Formation here consists of fluvial and eolian sandstone interbedded with shale.

Throughout northwestern Colorado, the Morgan Formation, Eagle Valley Evaporite, Minturn Formation, and Gothic Formation are overlain gradationally by the Maroon Formation (figs. 24 and 34). The main body of the Maroon Formation (fig. 36) consists of conglomerate, sandstone, siltstone, and mudstone, with thin intervals of limestone, and, locally, gypsum (Langenheim, 1954; Bass and Northrop, 1963, p. 46–54; Bryant, 1979, p. 29–40; Johnson, 1987). The clastic rocks predominantly are red, reddish brown, reddish orange, maroon, and purple. However, intervals of gray limestone and shale (interpreted as tongues of the Minturn and Gothic Formations) occur in the lower part of the main body of the Maroon Formation, and intervals of tan and light-gray quartz sandstone (interpreted either as tongues of the Schoolhouse Member or as diagenetically altered horizons) occur near the top of the main body of the Maroon Formation. Clastic layers typically are arkosic, micaceous, calcareous, and hematitic. Sandstone layers are well sorted to poorly sorted, very fine to coarse grained, and grade into conglomerate layers. Conglomerate layers contain clasts ranging from gravel to cobble size. Limestone layers, which usually are less than 3 ft thick, are most abundant in the lower part of the main body of the Maroon Formation. Typically, these carbonate rocks are fine grained and silty to muddy and grade into siltstone over distances of a few hundred feet. The main body of the Maroon Formation, in general, is characterized by extreme lenticularity, with individual beds no more than about 30 ft thick and traceable for no more than a mile.

South of the crest of the Uncompahgre Plateau and west of the crest of the San Juan Mountains, strata equivalent to the Minturn (or Gothic) and Maroon Formations grade into the upper member of the Hermosa Formation, Rico Formation, and Cutler Formation. From the Monument Upwarp west to the San Rafael Swell and High Plateaus, tongues of quartz sandstone alternate with red beds within the Cutler. The U.S. Geological Survey considers the quartz sandstone and red-bed sequences to be members of the Cutler Formation, whereas Baars (1962) assigned these sequences formation status and elevated the Cutler in the area to group rank. In ascending order, the formations comprising the Cutler Group in the southern two-thirds of the Monument Upwarp and vicinity are the Halgaito Shale, Cedar Mesa Sandstone, Organ Rock Shale, and White Rim Sandstone. As shown on plate 15, the Halgaito Shale in the northern Monument Upwarp and in areas to the west grades into the Elephant Canyon Formation. The Rico Formation north and west of the Monument Upwarp also grades into the Elephant Canyon Formation, but it becomes indistinguishable in the southeastern Henry Mountains Basin and eastern Kaiparowits Basin. The Organ Rock Shale pinches out in the vicinity of the San Rafael Swell, causing the Cedar Mesa and White Rim Sandstones to merge into a single body of sandstone (fig. 37), which in earlier reports was called either Coconino Sandstone (see, for example, Hunt and others, 1953) or Cedar Mesa Sandstone (see, for example, Baars, 1983), but is now referred to as White Rim Sandstone (the preferred usage in this report) or Toroweap Formation (George Billingsley, U.S. Geological Survey, written commun., 1988). The White Rim and Coconino Sandstones are included in the Weber–De Chelly zone and are described later in this report. The Cedar Mesa Sandstone is similar in lithology to the White Rim and Coconino Sandstones but is included in the Cutler-Maroon zone, because the Organ Rock Shale inhibits ground-water flow between the Weber–De Chelly and Cutler-Maroon zones.

The upper member of the Hermosa Formation consists of limestone, shale, sandstone, and conglomerate interbedded in

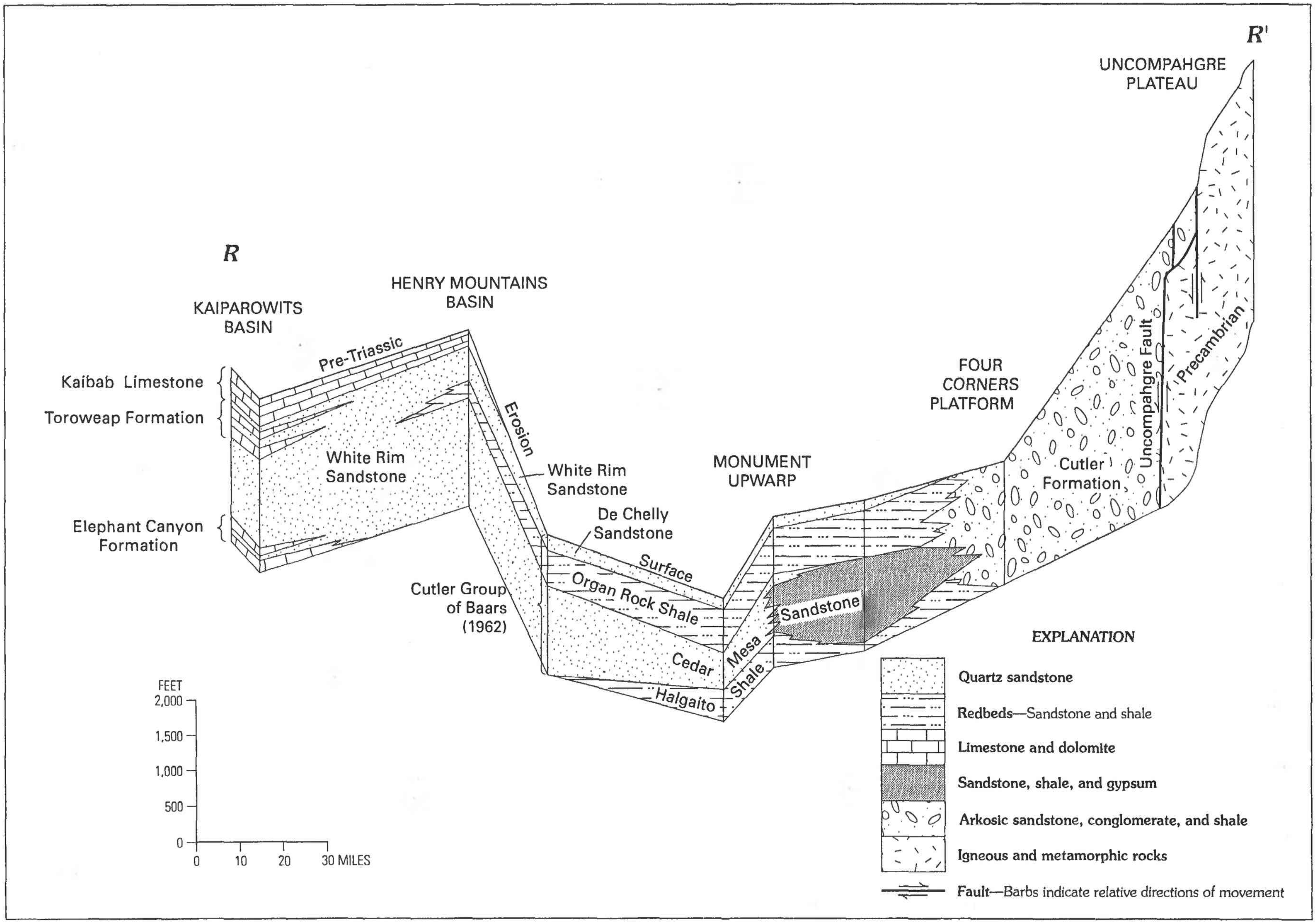



FIGURE 37.—Fence diagram showing relations among Permian formations in southwestern Colorado and southeastern Utah. Modified from Kunkel (1958, p. 165); location of section shown on plate 15.

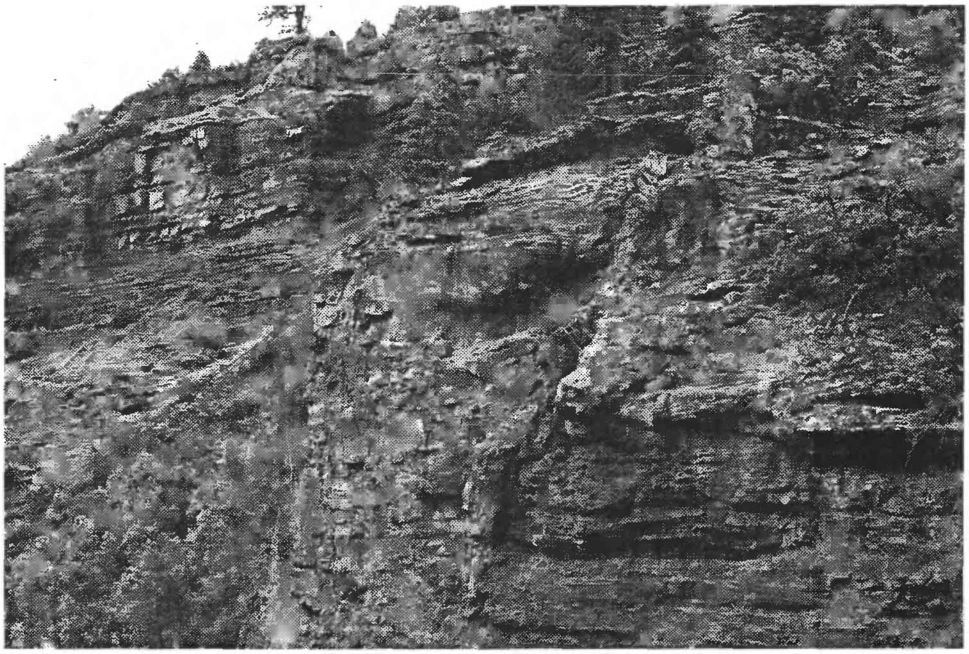


FIGURE 38.—Arkosic conglomerate, sandstone, and sandy siltstone in the Permian Cutler Formation along the Uncompahgre River in the San Juan Mountains, north of Ouray, Colo.

intervals a few feet to more than 50 ft thick. Nearly everywhere, the bottom of the member is characterized by an interval of sandstone with interbedded shale. Sandstone and conglomerate layers are thickest and most abundant in the vicinity of the San Juan Mountains and Uncompahgre Plateau. Carbonate layers increase in thickness and number westward and predominate in the southern Monument Upwarp. In the San Juan Mountains, the upper member of the Hermosa Formation consists of greenish-gray, brown, and maroon, micaceous sandstone; arkosic sandstone and conglomerate; and brownish-red, black, and green shale; with a few thin beds of gray limestone (Eckel and others, 1949, p. 10–12; Wengerd, 1957, p. 133; McKnight, 1974, p. 26–27; Baars and others, 1987, p. 347). Farther west, at the confluence of the Green and Colorado Rivers in the northern Monument Upwarp, the upper member of the Hermosa Formation consists of blue, greenish-gray, and gray limestone with chert concretions; gray, green, red, and purple mudstone, siltstone, and limy shale; and white, gray, greenish-gray, red, and purple limy, arkosic, and shaly sandstone (McKnight, 1940, p. 22–23). In the southern Monument Upwarp along the San Juan River, the upper member of the Hermosa Formation (fig. 31) predominantly consists of gray, finely crystalline, cherty limestone and red, purple, gray, and tan limy, sandy siltstone with a few thin layers of gray and brown, fine-grained, limy sandstone (Gregory, 1938, p. 64–65; Wengerd, 1963; O'Sullivan, 1965, p. 10–20).

The Rico Formation is transitional in lithology between the upper member of the Hermosa Formation and the Cutler Formation. Its top and bottom are distinguished by lithologic criteria that are not persistent throughout the area. In the San Juan Mountains, the Rico Formation consists of predominantly reddish brown, maroon, pink and gray, micaceous, and arkosic sandstone, pebbly sandstone, sandy shale and conglomerate, with thin intervals (less than 10 ft thick) of maroon, red, and gray, sandy and shaly limestone and black limy shale (Eckel and others, 1949, p. 13–15; Larsen and Cross, 1956, p. 46–47). In the northern Monument Upwarp, the Rico Formation similarly is composed of brownish-red, purple, maroon, brown, and gray sandstone, arkosic sandstone, sandy shale, and limy shale, with eight thin intervals of bluish-gray to greenish-gray nodular limestone (McKnight, 1940, p. 26–28). In the southern Monument Upwarp, the Rico Formation consists of reddish-brown, red, purple, and gray siltstone, with eight to nine intervals of fossiliferous, gray and white limestone and quartz sandstone. These eight to nine marker beds are 0–36 ft thick individually; intervening siltstone intervals are 16–136 ft thick (O'Sullivan, 1965, p. 23–31).

The Cutler Formation is 8,000 to more than 9,000 ft thick on the southwestern side of the Uncompahgre Plateau, but it pinches out abruptly to the north and east against faults bordering the plateau (fig. 37). The Cutler Formation consists of a coarse-grained arkosic facies from the Uncompahgre Plateau and San Juan Mountains to the northeastern Paradox Basin and a finer grained red-bed facies from the southwestern Paradox Basin to the Monument Upwarp and northeastern Arizona (Kunkel, 1960, p. 91–93). The coarse-grained facies (fig. 38) consists of massively bedded sandstone, grit, and conglomerate with interbeds of claystone, siltstone, and sandy shale and scattered interbeds of earthy, nodular limestone; the rocks are dominantly purplish red and reddish brown, but red, brown, orange, pink, and gray intervals, also, are present (Dane, 1935, p. 39–40; Eckel and others, 1949, p. 16–17; Bush and others, 1959, p. 309–312; Luedke and Burbank, 1962; McKnight, 1974, p. 30–31). The various rock types grade into each other and interfinger laterally over distances of a few thousand feet. The sandstone, grit, and conglomerate typically are arkosic and micaceous and commonly contain some calcite cement. Conglomerate layers, which are concentrated in the upper half of the formation, are composed of gravel- to boulder-sized clasts of igneous and metamorphic rocks in a matrix of coarse-grained, angular sandstone; the average size of the clasts and the number of conglomerate layers increase in a northeasterly direction toward the Uncompahgre Plateau. The finer grained facies consists of red, reddish-brown, brown, and purple, medium- to coarse-grained, arkosic sandstone, siltstone, and mudstone with some interbedded quartz sandstone, cherty limestone, and gypsum or anhydrite (Baker, 1933, p. 29–30; McKnight, 1940, p. 37–47; Shawe and others, 1968, p. 24–25). Quartz sandstone layers are most abundant near the base and top of the formation, where the Cutler Formation grades into the Cedar Mesa and De Chelly Sandstones.

The Halgaito Shale, which is about 750 ft thick (Baars, 1983, p. 83), consists of reddish-brown (mottled gray and green), fine-grained silty sandstone and siltstone with thin lenticular beds of gray limestone and, locally, interbeds of silt-pebble conglomerate, limestone conglomerate, gypsiferous sandstone, and gypsum (Gregory, 1938, p. 42; Kirkland, 1963, p. 84; Irwin and others, 1971, p. 23; Blakey, 1979, p. 119–120; Blakey and Baars, 1987, p. 362). The sandstone and siltstone are cemented with calcite. The formation characteristically is thinly bedded, with sandstone and shale beds commonly less than 1 ft thick and limestone and gypsum beds commonly less than 2 ft thick (Witkind and Thaden, 1963, p. 8; O'Sullivan, 1965, p. 34).

The Elephant Canyon Formation, which is as much as 1,500 ft thick, consists of tan and light-grayish-brown, crystalline to sucrose, cherty limestone; tan and beige, finely crystalline to chalky, cherty dolomite; and white, gray, and tan, fine-grained, quartz sandstone with red, purple, and green siltstone and mudstone, arkosic sandstone, and anhydrite (Kunkel, 1958, p. 163–164; Baars, 1979, p. 3). In the San Rafael Swell, limestone and sandstone in beds 3–50 ft thick underlie the White Rim Sandstone. Because of their stratigraphic position, these beds are interpreted in this report to be the top of the Elephant Canyon Formation, although Baker (1946), who first described them, interpreted the beds to be in the Hermosa Formation.

The Cedar Mesa Sandstone, for the most part, consists of light-gray, white, tan, beige, and grayish-orange, fine-grained quartz sandstone weakly to firmly cemented with calcite (Gregory, 1938, p. 43–45; Hunt and others, 1953, p. 41–42; Kunkel, 1958, p. 164–166; Thaden and others, 1964, p. 14–19; O'Sullivan, 1965, p. 36–46; Irwin and others, 1971, p. 24; Baars, 1979, p. 3; Blakey and Baars, 1987, p. 362). The sandstone typically occurs in layers 5–40 ft thick that display large-scale crossbedding (fig. 39). Reddish-brown, red, and greenish-gray siltstone and mudstone beds, 1–13 ft thick, are interbedded with the sandstone; many of these beds contain limestone nodules. Thin beds of bluish-gray limestone occurring in the formation are most numerous near the base and northwestern edge where the Cedar Mesa Sandstone grades into the Elephant Canyon Formation. Along its eastern edge, where it grades into the Cutler Formation, the Cedar Mesa Sandstone consists of red and purple gypsiferous shale, brownish-red and gray, friable, gypsiferous sandstone, gray and purple cherty limestone and conglomeratic limestone, and pink and white gypsum and anhydrite. The change from the quartz sandstone to the gypsiferous facies of the Cedar Mesa Sandstone is abrupt, occurring in a northeast-trending zone about 1 mi wide (Sears, 1956, p.

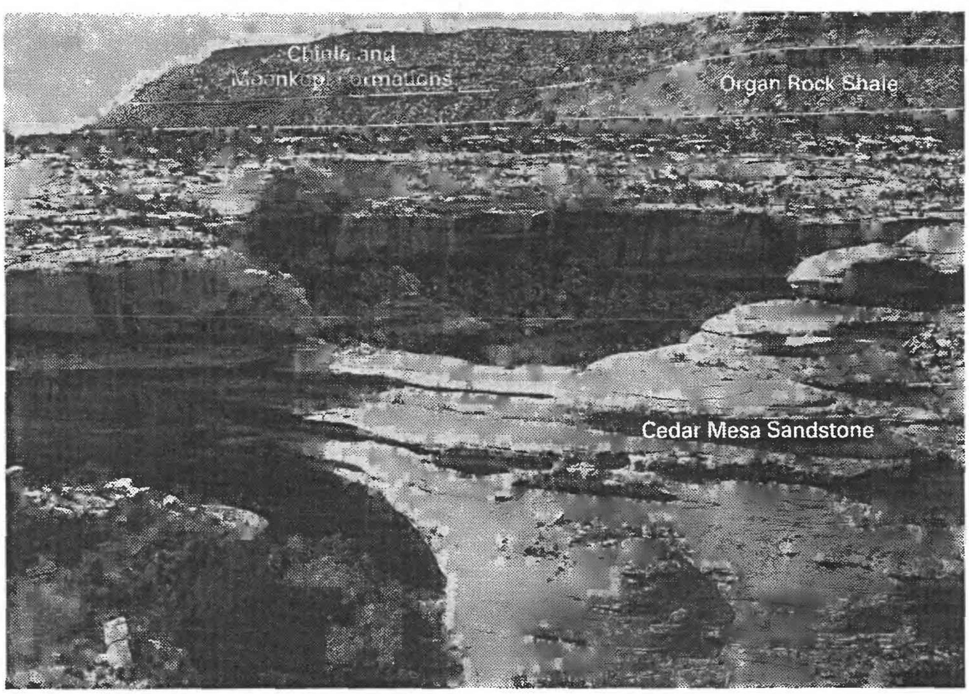



FIGURE 39.—Permian Cedar Mesa Sandstone and Organ Rock Shale (of Baars, 1962) at Natural Bridges National Monument, Utah.

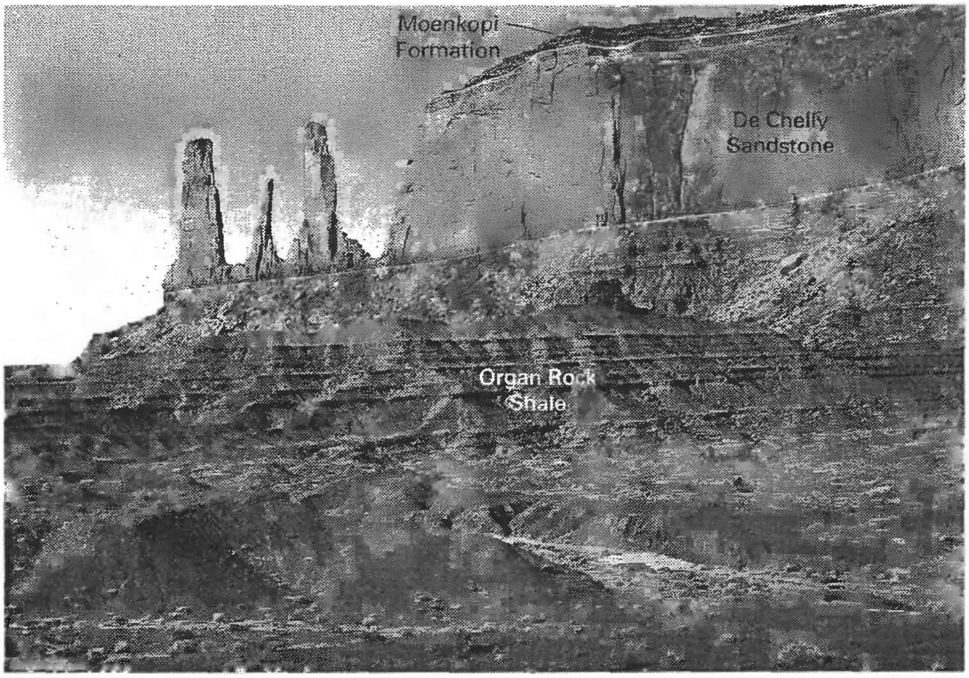



FIGURE 40.—Permian Organ Rock Shale (of Baars, 1962) and De Chelly Sandstone in Monument Valley, Utah.

184–187). The Cedar Mesa Sandstone is about 1,400 ft thick in the center of its depositional area (Baars, 1983, p. 85).

The Organ Rock Shale (fig. 40) consists of reddish-brown and orange-red (mottled gray and green) limy mudstone, siltstone, and very fine grained silty sandstone with beds of limestone-pellet conglomerate (Gregory, 1938, p. 46; Hunt and others, 1953, p. 42; Kunkel, 1958, p. 166; Mullens, 1960, p. 272–274; Witkind and Thaden, 1963, p. 10–12; Thaden and others, 1964, p. 19–29; Lewis and Campbell, 1965, p. 11–13; O'Sullivan, 1965, p. 46–49; Blakey, 1979, p. 121–122; Baars, 1987, p. 282; Blakey and Baars, 1987, p. 363). In Monument Valley, the formation contains thin beds of grayish-pink limestone. Along its northeastern edge where it grades into the Cutler Formation, the Organ Rock Shale contains layers of purple and red, coarse-grained, arkosic sandstone. Near the base and top of the formation where it grades into the Cedar Mesa and De Chelly Sandstones, the Organ Rock Shale contains layers of light-gray, white and pink, fine- to medium-grained quartz sandstone. These sandstone layers are crossbedded and as much as 40 ft thick. In general, bedding intervals vary from inches to more than 10 ft, but in many places, bedding is obscure. The Organ Rock Shale is more than 900 ft thick in the center of its depositional area (Baars, 1983, p. 88–89).

In the Defiance Plateau, the upper member of the Hermosa Formation pinches out, and the Rico Formation and Cutler Group grade into the Supai Formation. The Supai Formation consists of reddish-brown and reddish-orange, fine-grained sandstone, silty sandstone, and siltstone with beds of gypsiferous sandstone, siliceous limestone, and mudstone-pellet conglomerate (Read and Wanek, 1961; Irwin and others, 1971, p. 17–18). Some of the sandstone is crossbedded. A basal conglomerate consisting of gravel- to boulder-sized clasts of quartzite, granite, volcanic rocks, and limestone in a matrix of fine-grained sandstone is present in many places. This conglomerate layer is 2–5 ft thick. In general, the formation is thinly to thickly bedded.

In the Black Mesa, Kaibito, and Kaiparowits Basins, the upper member of the Hermosa Formation grades into the Wescogame Formation; the Halgaito Shale grades into the basal slope unit of the Esplanade Sandstone; the Cedar Mesa Sandstone grades into the main cliff and upper cliff-slope units of the Esplanade Sandstone; and the Organ Rock Shale grades into the Hermit Shale. The Wescogame Formation and Esplanade Sandstone are included in the Supai Group (fig. 2) as defined by McKee (1982).

The Wescogame Formation, which is 98–240 ft thick in the eastern Grand Canyon and Marble Canyon (McKee, 1982, p. 41), consists of reddish-brown, reddish-orange, pink, and red, fine-grained sandstone and siltstone with interbedded mudstone and limestone. Sandstone is the dominant constituent, but proportions of all rock types are extremely variable (McKee, 1982, p. 49).

The Esplanade Sandstone, which is 262–444 ft thick in the eastern Grand Canyon and Marble Canyon (McKee, 1982, p. 41), predominantly consists of very fine grained sandstone (McKee, 1982, p. 48). The basal slope unit is composed of reddish-brown, reddish-orange, red, and gray, very fine grained sandstone, siltstone, and mudstone, with a basal conglomerate layer 3–5 ft thick. The main cliff unit consists of grayish-white, gray, pale-orange, reddish-orange, reddish-brown, and pink, fine-grained, limy, crossbedded sandstone with interbeds of reddish-brown to red siltstone and mudstone and very sparse interbeds of limestone. The upper cliff-slope unit consists of interbedded sandstone, siltstone, and mudstone similar to rocks present in the other two units but eroded into a characteristic ledge and slope topography. According to Phoenix (1963, p. 10), sandstone beds in the upper unit typically are 2–10 ft thick.

The Hermit Shale (fig. 2) consists of thinly bedded, reddish-brown and reddish-orange mudstone, siltstone, and very fine grained sandstone with lenses of light-colored, fine-grained sandstone (Noble, 1922, p. 64–65; Phoenix, 1963, p. 10–11; McKee, 1982, p. 391–398). In the eastern Grand Canyon and Marble Canyon, the Hermit Shale is 76–710 ft thick (McKee, 1982, p. 36).

### CONTACTS

Contacts between geologic units that comprise the Cutler-Maroon zone of the Canyonlands aquifer and component geologic units of the underlying Four Corners confining unit generally are gradational. However, the Wescogame Formation rests on the eroded surface of the Manakacha Formation, which contains conglomerate-filled channels as much as 80 ft deep (McKee, 1982, p. 161). Where the Four Corners confining unit is missing because of erosion or nondeposition, particularly on the eastern and western fringes of the study area, component geologic units in the Cutler-Maroon zone unconformably overlie older geologic units. On the eastern side of the UCRB, the Maroon, Cutler, and Supai Formations overlie Precambrian igneous and metamorphic rocks in areas that were highlands intermittently before and during deposition. Such areas include the Gore Range, Uncompahgre Plateau, and Defiance Plateau. The relief on the basal unconformity in the Defiance Plateau ranges from 15 to 75 ft (Irwin and others, 1971, p. 18). Westward from the Monument Upwarp to the San Rafael Swell and Kaiparowits Basin, the Cutler Group progressively truncates older rocks, resting on Pennsylvanian rocks in the east and Mississippian rocks in the west (Kunkel, 1958, p. 164).

Contacts among geologic units comprising the Cutler-Maroon zone generally are conformable to gradational. The Minturn Formation is overlain conformably by the Maroon Formation (Tweto and Lovering, 1977, p. 55). The Gothic Formation is gradational into the Maroon Formation everywhere (Langenheim, 1952, p. 561; Bryant, 1979, p. 25). The upper member of the Hermosa Formation is overlain conformably by the Rico Formation, and a transition zone as much as 25 ft thick is present in most areas (Baker, 1933, p. 25; 1936, p. 21; Dane, 1935, p. 34; O'Sullivan, 1965, p. 23). The Rico Formation, in turn, grades laterally and vertically into the Cutler Group or Formation (Baker, 1933, p. 29; 1936, p. 29; 1946, p. 39; Dane, 1935, p. 41; McKnight, 1940, p. 49–50; 1974, p. 31; O'Sullivan, 1965, p. 35). Vertical shifts in the Rico-Cutler contact occur because fossiliferous limestone layers that define the top of the Rico Formation are discontinuous. As one of these limestone layers pinches out, the contact shifts vertically to the next fossiliferous limestone layer (Baker, 1946, p. 35–36).

The Cutler Formation grades into the Halgaito Shale, Cedar Mesa Sandstone, and Organ Rock Shale and becomes the Cutler Group. Within the Cutler Group, contacts between included formations generally are gradational vertically and laterally (fig. 37). The Halgaito Shale grades into the Elephant Canyon Formation. The Elephant Canyon Formation and Halgaito Shale grade into the Cedar Mesa Sandstone. The Cedar Mesa Sandstone generally grades into the Organ Rock Shale; in the southern Monument Upwarp, this transition zone is 60–100 ft thick (Mullens, 1960, p. 270). In the northern Monument Upwarp, however, the Cedar Mesa Sandstone–Organ Rock Shale contact is an irregular surface with as much as 40 ft of relief. Baker (1946, p. 39) interpreted this surface to be erosional, but Thaden and others (1964, p. 19) interpreted it as depositional.

Within the Supai Group and Hermit Shale, contacts between formations generally are unconformable. The Esplanade Sandstone overlies the Wescogame Formation unconformably. The contact surface contains conglomerate-filled channels as much as 50 ft deep (McKee, 1982, p. 161). The Esplanade Sandstone, in turn, is overlain unconformably by the Hermit Shale (Noble, 1922, p. 64). This unconformity is a very irregular surface with channels as much as 55 ft deep and hills as much as 114 ft high (Phoenix, 1963, p. 11; McKee, 1982, p. 161).

Contacts between geologic units in the Cutler-Maroon zone and geologic units in overlying zones of the Canyonlands aquifer north of the Uncompahgre Plateau generally are conformable to gradational, although local unconformities exist. The Ranchester Limestone Member of the Amsden Formation is overlain conformably to transitionally by the Tensleep Sandstone of Pennsylvanian and Permian age (Sando and others, 1975, p. 33). The Morgan Formation intertongues with and grades into the Weber Sandstone of Pennsylvanian and Permian age (Thomas and others, 1945; Untermann and Untermann, 1954, p. 33; Kinney, 1955, p. 44; Hallgarth, 1959; Bass and Northrop, 1963, p. 47–48; Hansen, 1965b, p. 50). Where the Schoolhouse Member of the Maroon Formation pinches out east of the White River Plateau, the main body of the Maroon Formation is overlain conformably to unconformably by the Permian and Triassic State Bridge Formation (Freeman, 1971, p. 4; Freeman and Bryant, 1977, p. 185). Atypically, the State Bridge, Maroon, and Gothic Formations are truncated from north to south in the Elk Mountains by an erosional surface on which the Jurassic Entrada Sandstone was deposited (Brill, 1944, p. 638; Langenheim, 1952, p. 563; 1954, p. 1755). This erosional surface also appears to truncate the Maroon Formation on the east side of the Gore Range (Lovering and Goddard, 1950, p. 36; Singewald, 1951, p. 10–13).

South of the Uncompahgre Plateau, the upper surface of the Cutler-Maroon zone is an unconformity in most areas where the undivided Cutler Formation or the Organ Rock Shale is at the top of the Paleozoic rocks. In the Uncompahgre Plateau, San Juan Mountains, and northern Paradox Basin, the Cutler Formation generally is overlain with angular discordance by the Dolores Formation of Triassic age; locally, in and near the San Juan Mountains, however, this contact is gradational (Eckel and others, 1949, p. 16; Bush and others, 1959, p. 308; Luedke and Burbank, 1962). In the central Monument Upwarp, the Organ Rock Shale is overlain disconformably by the Hoskinnini Member of the Triassic Moenkopi Formation (Read and Wanek, 1961, pl. 2; Thaden and others, 1964, p. 28–29).

Where the White Rim or De Chelly Sandstone is present, the contact with the underlying Cutler Formation or Organ Rock Shale generally is gradational. From the east side of the Monument Upwarp to the vicinity of the Colorado-Utah State line, the undivided Cutler Formation or Organ Rock Shale grades into the De Chelly Sandstone. According to Witkind and Thaden (1963, p. 12) and O'Sullivan (1965, p. 47), the Organ Rock–De Chelly transition occurs over a vertical distance of 25–65 ft. On the west side of the Monument Upwarp and in the eastern Henry Mountains Basin, contacts between the Organ Rock Shale and White Rim Sandstone are conformable to gradational (McKnight, 1940, p. 51; Hunt and others, 1953, p. 45; Steele-Mallory, 1982, p. 9).

The Supai Formation and Hermit Shale, also, are overlain conformably by Permian sandstones. In the Defiance Plateau area of northeastern Arizona, red beds of the Supai Formation are overlain transitionally by the De Chelly Sandstone (Read and Wanek, 1961, pl. 2; Irwin and others, 1971, p. 18). To the west, in the Lees Ferry area and in the Grand Canyon, the Hermit Shale conformably is overlain by the Coconino Sandstone of Permian age (Noble, 1922, p. 64; Phoenix, 1963, p. 11).

## WEBER–DE CHELLY ZONE

The Weber–De Chelly zone of the Canyonlands aquifer (pl. 16) consists almost entirely of quartz sandstone deposited in coastal dune fields, estuaries, and shoreline areas as the sea receded and then readvanced near the end of the Paleozoic Era (Kent, 1972; Mallory, 1972; Rascoe and Baars, 1972; Blakey, 1979; Fryberger and Koelmel, 1986). Component geologic units include the Wells Formation, Tensleep Sandstone, Weber Sandstone, Schoolhouse Member of the Maroon Formation (Johnson and others, 1990); Fryingpan Member of the Maroon Formation (Johnson, 1989); White Rim Sandstone (of Baars, 1962); De Chelly Sandstone, and Coconino Sandstone (table 1 and pl. 5).

Component geologic units in the Weber–De Chelly zone are sparsely fossiliferous. Nevertheless, their ages can be established fairly reliably on the basis of contained fossils (mainly fusulinids) and the ages of geological formations underlying, overlying, or intertonguing with the component geologic units. The existing evidence indicates that the Tensleep Sandstone and Wells Formation are mostly Middle and Upper Pennsylvanian (Desmoinesian to Virgilian); the Weber Sandstone is Middle Pennsylvanian to Lower Permian (Desmoinesian to Leonardian); and the Coconino, White Rim, and De Chelly Sandstones and the Schoolhouse and Fryingpan Members of the Maroon Formation are Lower Permian (Keefer and Van Lieu, 1966; Mallory, 1967; Irwin and others, 1971; Baars, 1979; Fryberger and Koelmel, 1986; Johnson, 1989; Johnson and others, 1990; Love and others, 1993.) Together, the variously named sandstone formations comprise a single, time-transgressive sequence that becomes progressively younger from north to south.

Component geologic units in the Weber–De Chelly zone thicken and thin more or less independently (pl. 16). The Tensleep Sandstone thickens from less than 200 ft to more than 700 ft concentrically toward the vicinity of Rock Springs, Wyo. The Wells Formation is about 300 ft thick at the eastern edge of the Overthrust Belt in Wyoming. On the basis of interpolation between data from boreholes in the UCRB and the type section of the Weber Sandstone in the Wasatch Range northwest of Salt Lake City, Utah, the Wells Formation appears to thicken westward to about 1,000 ft at the surface-water divide between the UCRB and the Basin and Range province. The Schoolhouse and Fryingpan Members of the Maroon Formation, together with the Weber Sandstone, comprise a depositional sequence that thickens westward from 0 ft in the Eagle Basin and Glenwood Springs areas of Colorado to about 1,600 ft in the western Uinta Mountains. Interpolation between outcrops in the western Uinta Mountains (Huddle and McCann, 1947b; Huddle and others, 1951) and an outcrop north of the Charleston Thrust Fault (Baker, 1964) indicates that the Weber Sandstone may be as much as 4,000 ft thick at the UCRB–Basin and Range divide west of Strawberry Valley. The White Rim Sandstone increases in thickness westward from 0 ft on the west side of the Monument Upwarp to more than 1,000 ft in the Capitol Reef–San Rafael Swell area. The De Chelly Sandstone is less than 200 ft thick in the Kaibito, Blanding, Paradox, and San Juan Basins, but thickens concentrically toward the Black Mesa Basin, where it is more than 1,000 ft thick. The Coconino Sandstone thins northward from about 600 ft in the eastern Grand Canyon to less than 100 ft in the Lees Ferry area of Arizona and probably pinches out in the southern Kaiparowits Basin (Hunt and others, 1953, p. 46).

Rocks comprising the Weber–De Chelly zone are missing in much of the study area south of the White River, east of the Green and Colorado Rivers, and north of the San Juan River. Geographic areas where the hydrogeologic unit is thin to absent include the Park Range, Gore Range, Front Range, White River Plateau, Elk Mountains, southern Piceance Basin, Uncompahgre Plateau, San Juan Mountains, northern and eastern Paradox Basin, and Monument Upwarp.

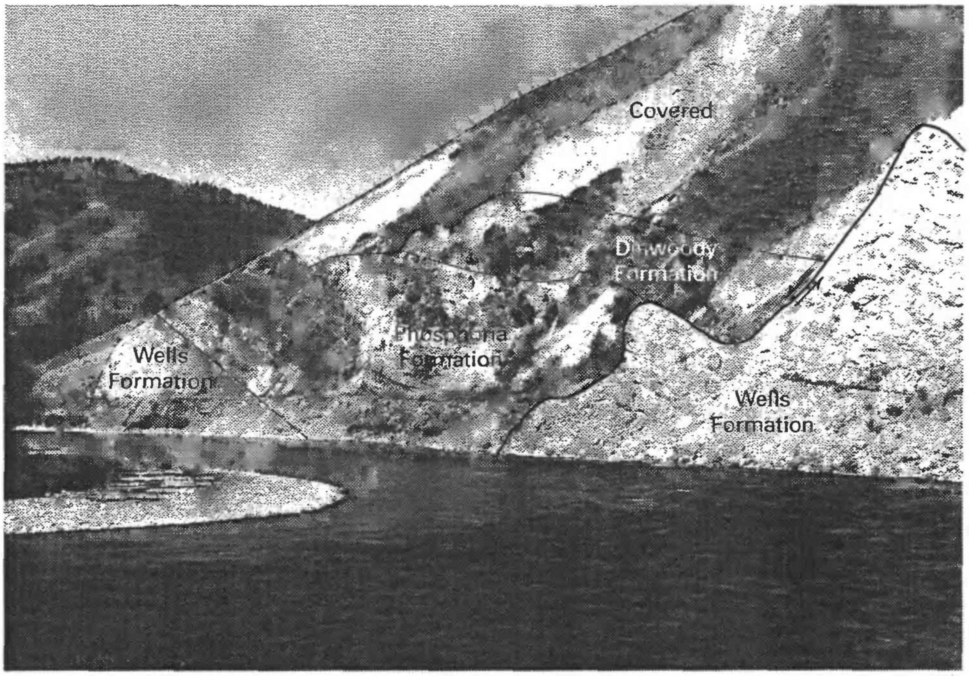



FIGURE 41.—Normal fault in the upper plate of the Darby Thrust Fault exposed by the Snake River as it cuts through the Salt River Range at Astoria Hot Springs, southwest of Jackson, Wyo. The Pennsylvanian and Permian Wells Formation on the right has been uplifted against the Permian Phosphoria Formation and Triassic Dinwoody Formation on the left (downstream) side of the fault. This interpretation is based in part on written communication from James A. Peterson of the University of Montana (1988).

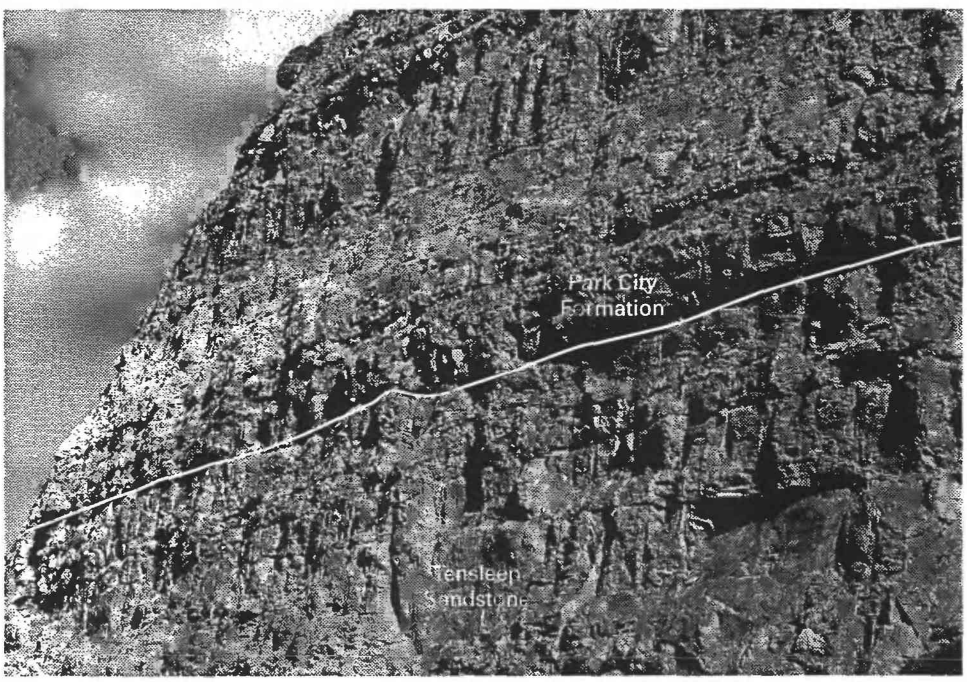



FIGURE 42.—Pennsylvanian Tensleep Sandstone overlain by interbedded carbonate rocks and sandstone of the Permian Park City Formation, east flank of Wind River Mountains, northwest of Dubois, Wyo.

COMPONENT GEOLOGIC UNITS

In the Overthrust Belt and western Green River Basin of Wyoming, rocks comprising the Weber–De Chelly zone are assigned to the Wells Formation. The Wells Formation (fig. 41) consists of massively bedded, light-gray, tan, and pink, quartzitic, fine-grained, quartz sandstone with thin interbeds of fine-grained dolomite and limestone and dark-gray mudstone (Wanless and others, 1955, p. 34–35; Oriel, 1969, p. 8; Rubey and others, 1975, p. 3). Generally less than 20 ft thick, the carbonate intervals thicken and become more numerous westward, and comprise as much as 30 percent of the formation at the UCRB–Basin and Range divide.

The Wells Formation grades into the Tensleep Sandstone along an axis of thinning that extends longitudinally through the western Green River Basin. The Tensleep Sandstone (fig. 42) consists of crossbedded, light-gray, tan, and white, fine-grained, friable to quartzitic or calcareous, quartz sandstone with thin interbeds of chert and fine-grained dolomite and limestone (Foster, 1947, p. 1558; Gudim, 1956, p. 70; Berry, 1960,


FIGURE 43.—Northeast-dipping beds of Pennsylvanian and Permian Weber Sandstone in Irish Canyon, Colo., at the eastern end of the Uinta Mountains. The full thickness of the formation is exposed. (In the left foreground is an outcrop of cherty limestone and sandstone of the Pennsylvanian Morgan Formation.)

p. 15; Keefer and Van Lieu, 1966, p. 40; Mallory, 1967, p. 21). The carbonate layers, which comprise as much as 20 percent of the formation, are concentrated in the lower part; they generally are less than 10 ft thick and either pinch out laterally or grade into sandstone.

South of the Green River and Washakie Basins, the Tensleep Sandstone and Wells Formation thin and grade into the Weber Sandstone (fig. 43). In the western Uinta Mountains and Uinta Basin, the Weber Sandstone is a marine deposit consisting of light-gray and white, fine-grained, friable to quartzitic or calcareous, quartz sandstone with thin interbeds of fine-grained, finely crystalline, and sandy limestone and dolomite, and maroon, brown, and gray siltstone and mudstone (Huddle and McCann, 1947b; Fryberger and Koelmel, 1986). Generally less than 30 ft thick, the carbonate intervals thicken and become more numerous southward, and comprise as much as 30 percent of the formation in the western Uinta Basin and Wasatch Plateau. In the vicinity of the Whiterocks River, marine beds interfinger with and grade into an eolian facies of the Weber Sandstone (fig. 44), which consists of massively crossbedded, light-gray, tan, and white, fine- to medium-grained, friable to quartzitic or calcareous, quartz sandstone (Untermann and Untermann, 1954, p. 36; Kinney, 1955, p. 46; Ritzma, 1959, p. 26; Hansen, 1965b, p. 49).

North and west of the White River Plateau, the Weber Sandstone either terminates abruptly against the Maroon Formation (Johnson and others, 1990) or, as depicted in figure 44, thins and grades into eolian and fluvial beds that intertongue with the Maroon Formation and gradually lose their identity in the eastern Eagle Basin (Fryberger and Koelmel, 1986). The uppermost tongue of this eolian/fluvial sequence traditionally has been called the Schoolhouse Tongue of the Weber Sandstone (Maughan, 1980), based on the interpretation that it represents a natural transition from the dune fields farther west to the alluvial fan deposits of the Maroon Formation. The natural transition is caused by increasing proximity to the source of the sediment, the ancestral Rocky Mountains. The Schoolhouse Tongue, which has a maximum thickness of about 220 ft, consists of planar to crossbedded, yellowish-gray, gray, and white, fine- to coarse-grained, calcite- or quartz-cemented, commonly petroliferous, subarkosic to arkosic sandstone with micaceous intervals and interbeds of greenish-gray and red shale (Brill, 1944; Hallgarth, 1959; Bass and Northrop, 1963; Fryberger and Koelmel, 1986). On the basis of extensive field work and petrological examination, Johnson and others (1990) concluded that the Schoolhouse Tongue differed from red eolian deposits near the top of the Maroon Formation only in color. According to Johnson and others (1990), the Schoolhouse Tongue and other tongues of light-colored sandstone near the top of the Maroon Formation were originally red but were bleached by hydrocarbons migrating from the Belden Formation up a fault in the East Rifle Creek area and then laterally through the Maroon Formation. Consequently, the Schoolhouse Tongue was not to be considered an extension of the Weber dune field but diagenetically altered Maroon Formation, and Johnson and others (1990) renamed the Schoolhouse Tongue, the Schoolhouse Member of the Maroon Formation. At the time of this writing (1990), a consensus of opinion regarding the origin and naming of the Schoolhouse rocks has not been reached.

In the Elk Mountains and southeastern White River Plateau, a layer of crossbedded, light-brown and reddish-orange, very fine grained to medium-grained quartz sandstone occurs

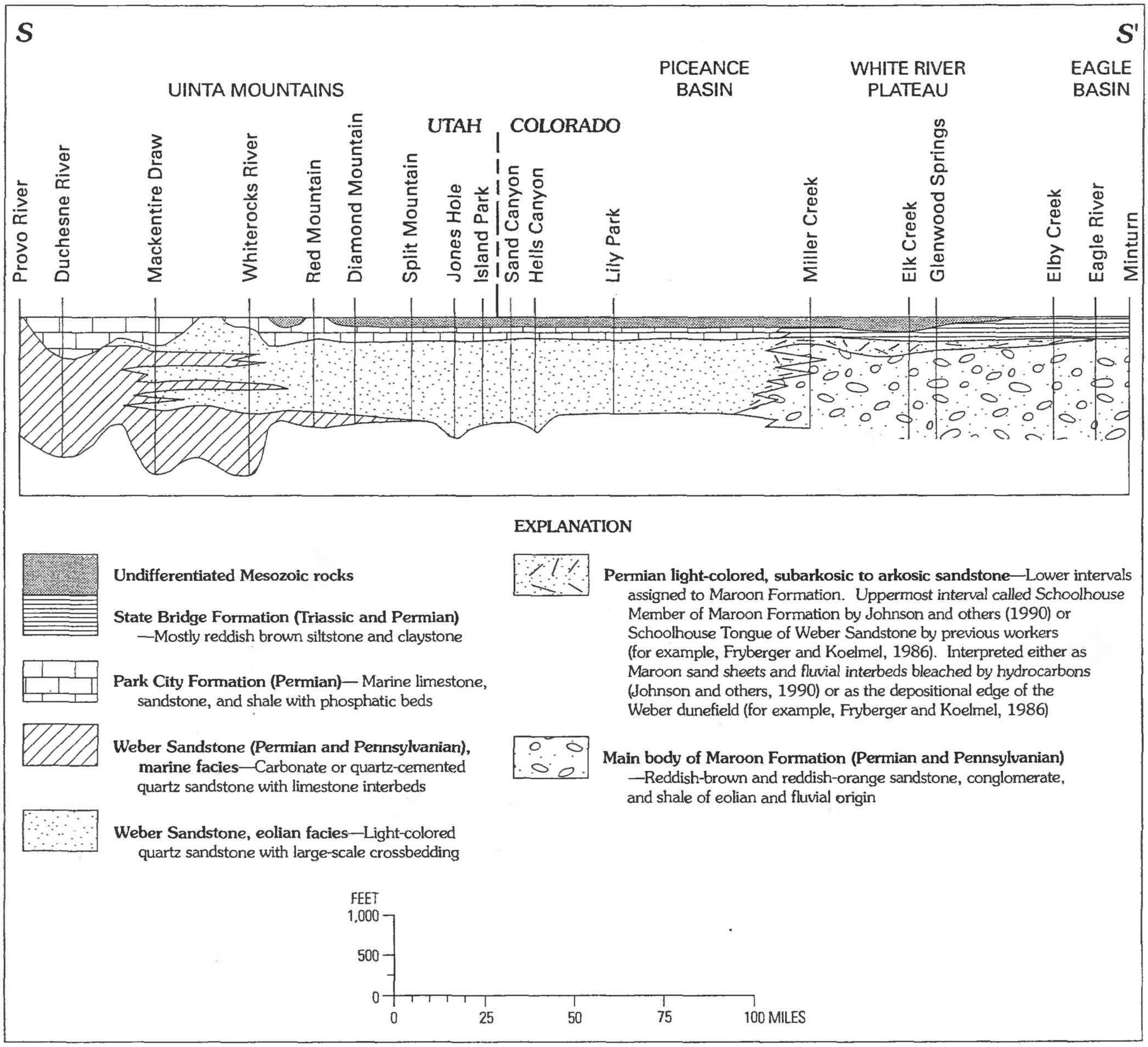



FIGURE 44.—Stratigraphic section showing facies changes within the Weber Sandstone and Maroon Formation in Utah and Colorado. Modified from Fryberger and Koelmel (1986); location of section shown on plate 16.

between the Maroon Formation and typical reddish-brown siltstone beds of the State Bridge Formation. This sandstone, which Freeman (1971) called the sandstone of the Fryingpan River and included in the State Bridge Formation, has a maximum thickness of 400 ft. Johnson (1989) recognized that the sandstone of the Fryingpan River is related more to eolian deposits near the top of the Maroon Formation, such as the Schoolhouse Member, than to the coastal plain deposits that typify the State Bridge Formation (Bryant and Martin, 1988) and renamed the sandstone the Fryingpan Member of the Maroon Formation. According to Johnson (1989), the Fryingpan Member is the remnant of a dune field that accumulated against an ancestral Sawatch Range. This dune field may have been as much as 80 $mi^2$ in area, but its eastern half has been removed by erosion. The current northern, western, and southern limits of the Fryingpan Member are depositional pinchouts.

The Weber Sandstone grades into the White Rim Sandstone along an axis of thinning extending from the southern end of the Uinta Basin southwesterly to the Wasatch Plateau. In the San Rafael Swell, Capitol Reef Fold and Fault Belt, and Circle Cliffs Uplift, the White Rim Sandstone (called Coconino Sandstone in some older U.S. Geological Survey reports) consists of gray, tan, and white, massively crossbedded, friable to carbonate-cemented, very fine grained to fine-grained quartz

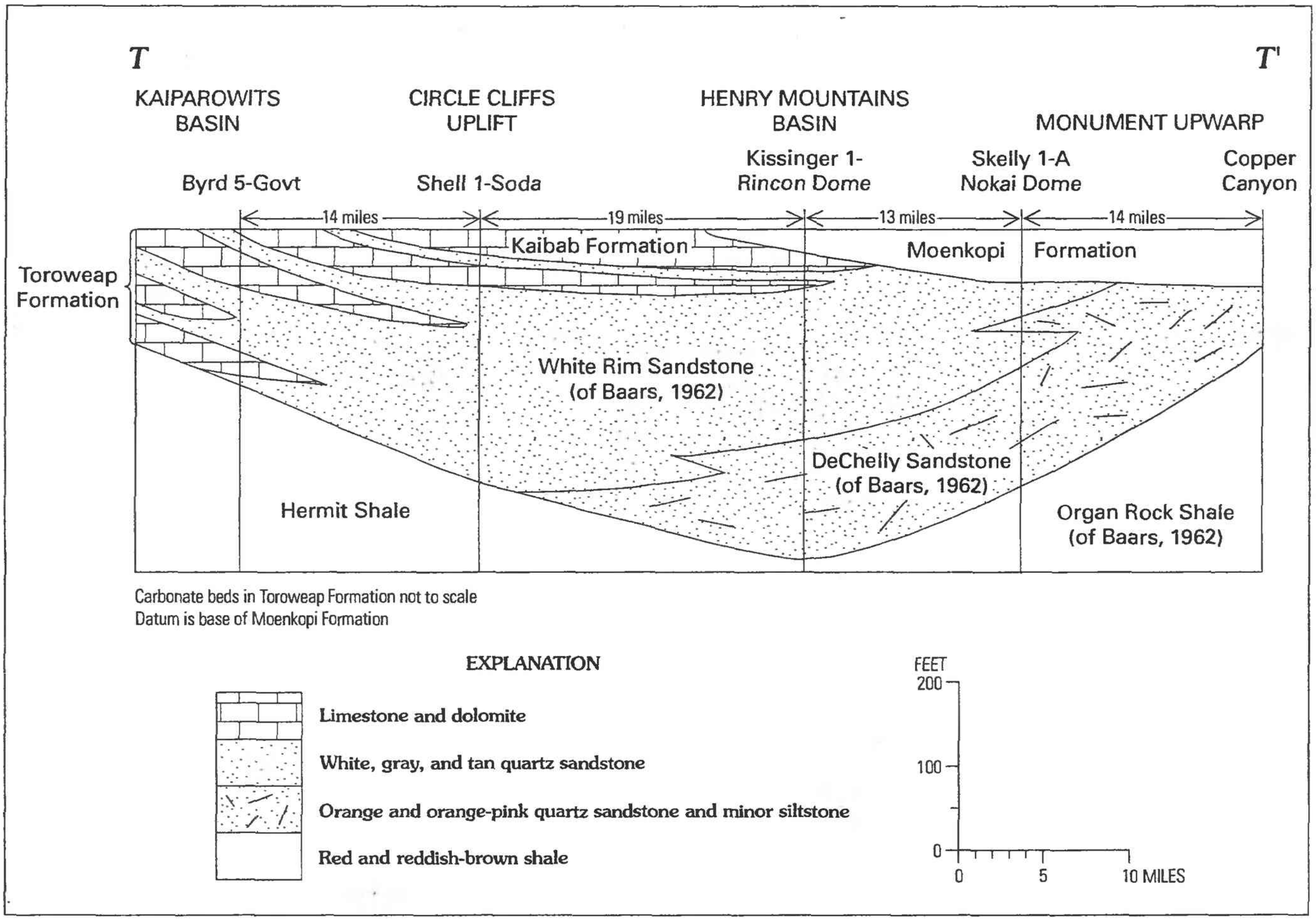



FIGURE 45.—Stratigraphic section showing relations among Permian formations in southeastern Utah. Location of section shown on plate 16.

sandstone (Gilluly, 1929; Gregory and Moore, 1931; Baker, 1946; Hunt and others, 1953; Smith and others, 1963; Davidson, 1967). To the east, in the Monument Upwarp, the White Rim Sandstone generally is a white, pale-yellow, and light-gray, crossbedded, fine-grained, friable to carbonate-cemented, petroliferous, quartz sandstone (McKnight, 1940; Baker, 1946; Hunt and others, 1953; Baars and Seager, 1970; Steele-Mallory, 1982; Baars, 1987). At its depositional edge in the White Canyon area of the Monument Upwarp, the White Rim Sandstone consists of pale-orange, silty sandstone and sandy siltstone (Thaden and others, 1964, p. 29).

South and west of the Circle Cliffs Uplift, the White Rim Sandstone grades into interbedded carbonate rocks, sandstone, shale, and anhydrite of the Permian Toroweap Formation and ceases to be an identifiable unit (fig. 45). However, as the White Rim Sandstone loses its identity, another sandstone body, the Coconino Sandstone, appears beneath the Toroweap Formation and thickens southward toward the Grand Canyon. A third sandstone body in the area, the De Chelly Sandstone, underlies and interfingers with the Coconino Sandstone and equivalent strata from the Defiance Plateau to central Arizona. According to Blakey (1979), the main body of the De Chelly Sandstone and its equivalent in central Arizona, the Schnebly Hill Formation, were deposited in a small basin centered about Holbrook, Ariz. (location shown on pl. 1). With increasing aridity, progradation of inland dunes across coastal beach areas and mud flats resulted in accumulation of the Coconino Sandstone on top of the Schnebly Hill Formation on the west side of the Holbrook Basin and the Black Creek Member of the De Chelly Sandstone on the east side of the Holbrook Basin (Blakey, 1979; Blakey and Middleton, 1987). The Schnebly Hill Formation and the Black Creek Member of the De Chelly Sandstone do not extend into the study area and are not discussed further.

The Coconino Sandstone, where it crops out in Marble Canyon, the canyon of the Little Colorado River, and the Grand Canyon (fig. 2) is a massively crossbedded, light-tan to yellowish-gray, silica-cemented, fine- to medium-grained, quartz sandstone (Noble, 1922, p. 66–67; Phoenix, 1963, p. 11). The De Chelly Sandstone in the UCRB is distinguished from the Coconino Sandstone mainly by a change to a predominantly pale orange color. In Monument Valley and along Comb Ridge, the De Chelly Sandstone (fig. 40) consists of crossbedded, reddish-orange, pale-orange, tan, and gray, fine- to medium-grained, friable to quartzitic or calcareous, quartz sandstone with red shale layers near the base that are transitional into the Organ Rock Shale (Baker, 1936; Gregory, 1938; Mullens, 1960; Read and Wanek, 1961; Witkind and Thaden, 1963; O'Sullivan, 1965; Irwin and others, 1971; Blakey and Baars, 1987). South of Canyon de Chelly in the Defiance Plateau, the De Chelly Sandstone is split by an interval of red and brownish-orange, calcareous siltstone and silty sandstone that thickens southward and merges with the Supai Formation (Read and Wanek, 1961, p. 4–6). Pierce (1964) termed this interval the Oak Springs Member and the underlying and overlying sandstone intervals the Hunters Point and White House Members. The Hunters Point Member consists of reddish-orange, evenly bedded, silty quartz sandstone, whereas the White House Member is slightly feldspathic but otherwise identical to the De Chelly Sandstone of the Monument Upwarp (Blakey, 1979, p. 123–124).

### UPPER CONTACTS

Contacts between geologic units comprising the Weber–De Chelly zone and overlying Permian and Triassic formations generally are conformable but vary with the tectonic setting. The Wells Formation grades laterally into the Grandeur Member of the Phosphoria Formation (Peterson, 1984, p. 46). However, the Tensleep Sandstone generally is overlain disconformably by the Permian Phosphoria and Park City Formations and the Permian and Triassic Goose Egg Formation (Keefer and Van Lieu, 1966, p. 41; Mallory, 1967, p. 25). In the Uinta Mountains, the Weber Sandstone is overlain gradationally to disconformably by the Park City Formation (Thomas and others, 1945; Huddle and McCann, 1947b; Hansen, 1965b, p. 58). However, equivalents of the Weber Sandstone in northwest Colorado, the Schoolhouse and Fryingpan Members of the Maroon Formation, are overlain unconformably by the Permian and Triassic State Bridge Formation (Johnson, 1989; Johnson and others, 1990). On the west side of its depositional area, the White Rim Sandstone generally is overlain conformably to gradationally by either the Toroweap or Kaibab Formation of Permian age (Gregory and Moore, 1931; Baker, 1946; Hunt and others, 1953; Smith and others, 1963; Davidson, 1967). In the San Rafael Swell, however, the White Rim Sandstone is overlain unconformably by either the Kaibab Formation (Welsh and others, 1979, p. 143) or, where erosion has removed the Kaibab Formation, the Triassic Moenkopi Formation (Gilluly, 1929, p. 81; Hawley and others, 1965, p. 17). East of where the Kaibab Formation terminates, the White Rim Sandstone generally is overlain unconformably by the Moenkopi Formation (Hunt and others, 1953, p. 45; Baars and Seager, 1970, p. 714), but in the vicinity of the confluence of the Green and Colorado Rivers, the White Rim Sandstone is overlain conformably by red beds that have been interpreted as either Cutler Formation or Moenkopi Formation (Steele, 1987, p. 5). On the Monument Upwarp and Defiance Plateau, the De Chelly Sandstone is overlain disconformably but with increasing hiatus southward by either the Hoskinnini Member of the Moenkopi Formation or the Shinarump Member of the Upper Triassic Chinle Formation (Mullens, 1960, p. 274–275; Read and Wanek, 1961, pl. 2). High-angle crossbeds of the Coconino Sandstone in the Lees Ferry area are truncated by flat-lying beds of the Toroweap Formation (Phoenix, 1963, p. 12), but the contact between the two formations in Marble Canyon and the Grand Canyon generally is interpreted to be conformable (Beus and Lucchita, 1987, p. 7).

## PARK CITY–STATE BRIDGE ZONE

The Park City–State Bridge zone of the Canyonlands aquifer (pl. 17) consists of carbonate, clastic, and evaporite sediments deposited in a shallow sea, marginal restricted basins, and coastal lowlands during a fifth and final Paleozoic marine advance (Kent, 1972; Rascoe and Baars, 1972; Peterson, 1984). Component geologic units include the Kaibab, Toroweap, Park City, and Phosphoria Formations; and Permian parts of the Permian and Triassic Goose Egg and State Bridge Formations (table 1 and pl. 5). Following McKelvey and others (1959), the Park City, Phosphoria, and Goose Egg Formations in this report are named according to the prevailing rock types that, in varying proportions, are common to all three formations. Subdivisions of the Park City and Phosphoria Formations are called "members." Where members of either formation extend into the other formation, they are called "tongues."

Permian and Triassic parts of the Goose Egg and State Bridge Formations are distinguished by limestone intervals that pinch out eastward. In the Goose Egg Formation, the uppermost Permian horizon is the Ervay Limestone Member (Maughan, 1980, p. 106; Peterson, 1984, p. 28). Where the Ervay Limestone Member pinches out, it is impossible to distinguish the Permian-Triassic boundary. Similarly, the top of the Permian cannot be identified reliably in the State Bridge Formation in the absence of the South Canyon Creek Dolomite Member. In the absence of paleontological information, the top of the Park City–State Bridge zone where either the Goose Egg or State Bridge Formation comprises the zone generally was chosen in this report as the stratigraphically highest carbonate interval present in measured surface sections and borehole logs. If no carbonate beds were present, the entire Goose Egg or State Bridge Formation was assigned to the Chinle-Moenkopi confining unit (of Freethey and Cordy, 1991, table 1). Parts of the Goose Egg and State Bridge Formations included in the Park City–State Bridge zone, respectively, are called the lower part of the Goose Egg Formation and lower part of the State Bridge Formation in this report.

Abundant paleontological evidence (mainly brachiopods, pelecypods, gastropods, cephalopods, scaphopods, fusulinids, conularids, and conodonts) indicates that component geologic units in the Park City–State Bridge zone are entirely Permian in age. The Park City and Phosphoria Formations are Lower to Upper Permian (Leonardian to Guadalupian) according to McKelvey and others (1959, p. 36–40) and Peterson (1984, p. 28). Similarly, the lower parts of the Goose Egg and State Bridge Formations are Lower to Upper Permian (Bass and Northrop, 1963, p. 47–49; Maughan, 1980, p. 106–109; Peterson, 1984, p. 25). The Toroweap Formation is a Lower Permian deposit, and the overlying Kaibab Formation is a Lower to Upper Permian deposit (Hallgarth, 1967; Rascoe and Baars, 1972). The Kaibab Formation becomes younger from southwest to northeast, either as a result of northwesterly onlap (Heylmun, 1958, p. 1800; Smith and others, 1963, p. 10) or southwesterly erosion (Baker, 1946, p. 52–53).

The Park City–State Bridge zone is restricted, because of erosion or nondeposition, to the northern and western parts of the UCRB (pl. 17). North of the Uinta Mountains, the Park City and Phosphoria Formations thicken from less than 300 ft on the Rock Springs Uplift to more than 500 ft in the Washakie Basin and more than 600 ft in the Overthrust Belt. In the southern Uinta Mountains and Uinta Basin, the Park City Formation thickens westward from less than 100 ft on the Yampa Plateau to about 550 ft at the UCRB–Basin and Range divide (below the Charleston Thrust Fault). The Park City Formation also thickens eastward from the Yampa Plateau and is more than 500 ft thick where it grades into the lower part of the State Bridge Formation in the northwestern corner of the White River Plateau. The lower part of the State Bridge Formation is more than 400 ft thick in the northern White River Plateau but becomes thinner in all directions away from this area. The eastern equivalent of the Park City and Phosphoria Formations in Wyoming, the lower part of the Goose Egg Formation, generally is less than 300 ft thick. Equivalents of the Park City Formation, south of the San Rafael Swell, the Toroweap and Kaibab Formations, thicken westward from 0 ft near the Colorado and Green Rivers to about 800 ft in the High Plateaus region.

## COMPONENT GEOLOGIC UNITS

The lower part of the Goose Egg Formation comprises the Park City–State Bridge zone from the vicinity of Steamboat Springs, Colo., to north of the Rawlins Uplift in Wyoming, along the northeastern edge of the study area. The lower part of the Goose Egg Formation (fig. 46) consists of the Opeche Shale, Minnekahta Limestone, Glendo Shale, Forelle Limestone, Difficulty Shale, and Ervay Limestone Members (fig. 47). The carbonate members, which generally are interpreted as tongues of the Park City Formation (Maughan, 1980; Peterson, 1984), typically are 6–22 ft thick; intervening shale members typically range in thickness from 40 to 100 ft (Keefer and Van Lieu, 1966, p. 49). Carbonate members in the Rawlins Uplift typically consist of gray to purplish-gray, very fine grained to crystalline limestone and shaly limestone (Berry, 1960, p. 67–68). Carbonate members in the northern Great Divide Basin range from limestone to dolomite in composition (Thomas, 1951, p. 35–36). Shale members in the Goose Egg Formation typically consist of red and reddish-brown siltstone and mudstone with thin layers of fine- to medium-grained sandstone, gypsum, anhydrite, and carbonate rocks (Thomas, 1951, p. 35–36; Gudim, 1956, p. 70–71). In the Rawlins Uplift and other areas at the western limits of the Goose Egg Formation, many of the shale layers are green or greenish gray (Berry, 1960, p. 16). Accompanying this color change, carbonate and chert interbeds thicken and become more numerous. At Green

FIGURE 46.—Pennsylvanian Tensleep Sandstone and Permian to Triassic Goose Egg Formation dipping northeasterly in the upper plate of the Bell Springs Thrust Fault, north of Rawlins, Wyo.

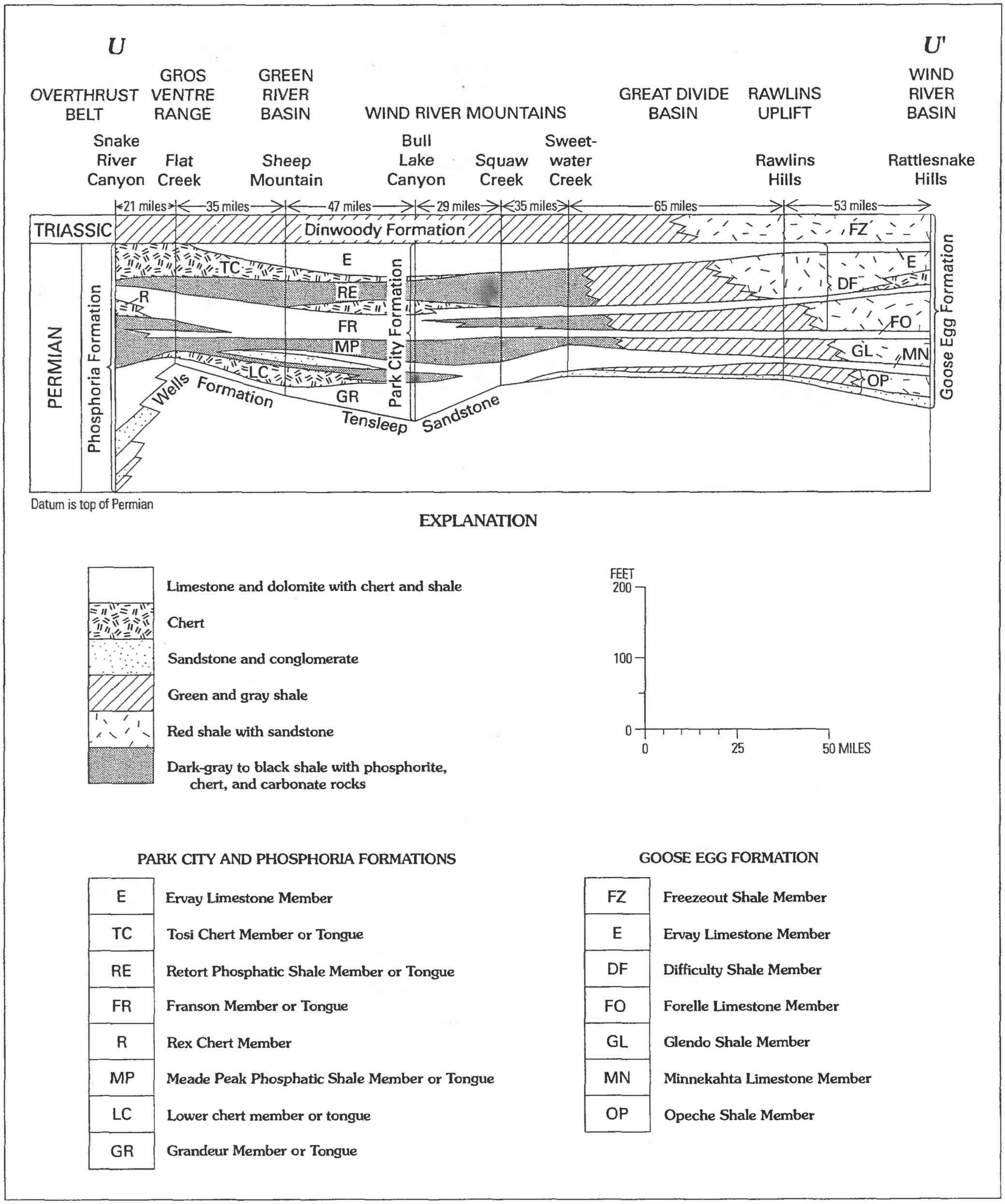



FIGURE 47.—Stratigraphic section showing relations among Permian formations in southwestern Wyoming. Modified from McKelvey and others (1959) based on reports by Richmond (1945), Foster (1947), Wanless and others (1955), Berry (1960), Keefer and Van Lieu (1966), and Peterson (1984); location of section shown on plate 17.

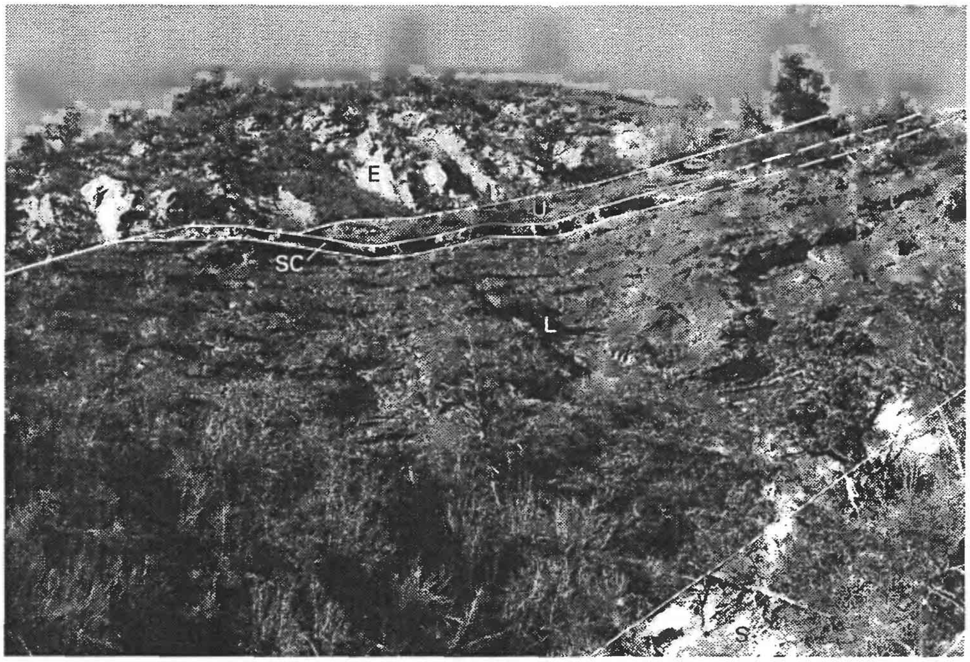



FIGURE 48.—Permian lower part of the State Bridge Formation underlain by Permian Schoolhouse Member of the Maroon Formation and overlain by Mesozoic rocks on South Canyon Creek west of Glenwood Springs, Colo. S, Schoolhouse Member of Maroon Formation; L, lower shale member of State Bridge Formation; SC, South Canyon Creek Dolomite Member of State Bridge Formation. U, upper shale member of State Bridge Formation and Chinle Formation (Triassic); E, Entrada Sandstone (Jurassic).

Mountain on the Sweetwater Arch, for example, carbonate and chert layers comprise the upper fourth of the Goose Egg Formation (Thomas, 1951, p. 36).

From the southern Sand Wash Basin to the Elk Mountains, strata equivalent to the lower part of the Goose Egg Formation arbitrarily are assigned to the lower part of the State Bridge Formation. The lower part of the State Bridge Formation (fig. 48) includes the lower shale member and the South Canyon Creek Dolomite Member. The lower shale member, which makes up most of the lower part of the State Bridge Formation, consists of thinly bedded, micaceous, limy siltstone and claystone with interbeds of fine- to medium-grained sandstone that become coarser and more numerous southward (Brill, 1944, p. 635; Donner, 1949, p. 1228–1229; Bass and Northrop, 1963, p. 48–49; Freeman, 1971; Freeman and Bryant, 1977; Maughan, 1980, p. 109). The lower shale member typically is reddish brown, brownish red, and red but contains yellow and greenish-gray intervals along its western margin, from the vicinity of State Bridge, Colo., to the southwestern White River Plateau. The South Canyon Creek Dolomite Member, which is equivalent to the Franson Member of the Park City Formation and the Forelle Limestone Member of the Goose Egg Formation (Maughan, 1980), is 1–10 ft thick in measured sections (Stewart and others, 1972b, p. 46–47). The South Canyon Creek Dolomite Member consists of gray and white, sandy and shaly, algal limestone and dolomite (Brill, 1944, p. 635; Donner, 1949, p. 1228–1229; Bass and Northrop, 1963, p. 48–49); where the member pinches out east of Eagle, Colo., and south of the Fryingpan River (Freeman and Bryant, 1977, p. 186), the lower and upper shale members of the State Bridge Formation become indistinguishable.

The Goose Egg and State Bridge Formations grade laterally into the greenish-gray shale facies of the Park City Formation (fig. 49). In drill holes and in surface sections described by Brill (1944, p. 640–642), this facies predominantly consists of dark-gray, greenish-gray, and olive-green gypsiferous siltstone and mudstone with intervals of fine-grained sandstone, limestone, and dolomite. Intervals of red and yellow shale and sandstone persist from the Goose Egg and State Bridge Formations. This facies, on the basis of limited subsurface data, appears to comprise most of the Park City Formation in the Sand Wash, Washakie, and Great Divide Basins. On the southeastern flank of the Uinta Mountains, the facies comprises the upper half of the formation (Untermann and Untermann, 1954, p. 38; Schell and Yochelson, 1966; Hansen and others, 1983). West of Dinosaur National Monument, the greenish-gray shale facies becomes a tongue in the Franson Member of the Park City Formation (fig. 49) and changes back into a predominantly red siltstone and sandstone interval. This red-bed interval is called the Mackentire Tongue of the Woodside Shale (Huddle and others, 1951; Kinney, 1955, p. 49–51; McKelvey and others, 1959, p. 34–35).

Over most of its extent, from the Uinta Mountains to the Uinta Basin, the Park City Formation consists of three stratigraphic intervals: the Grandeur Member, the Meade Peak Phosphatic Shale Tongue of the Phosphoria Formation, and the Franson Member (figs. 47, 49, 50). The Grandeur Member and Meade Peak Phosphatic Shale Tongue successively pinch out eastward from a line extending through the east-central Uinta Mountains to the Rock Springs Uplift (Peterson, 1984, fig. 12). In the Wind River Mountains and on the northern edge of the Green River Basin, the Franson Member is overlain by the Tosi Chert and Retort Phosphatic Shale Tongues of the Phosphoria

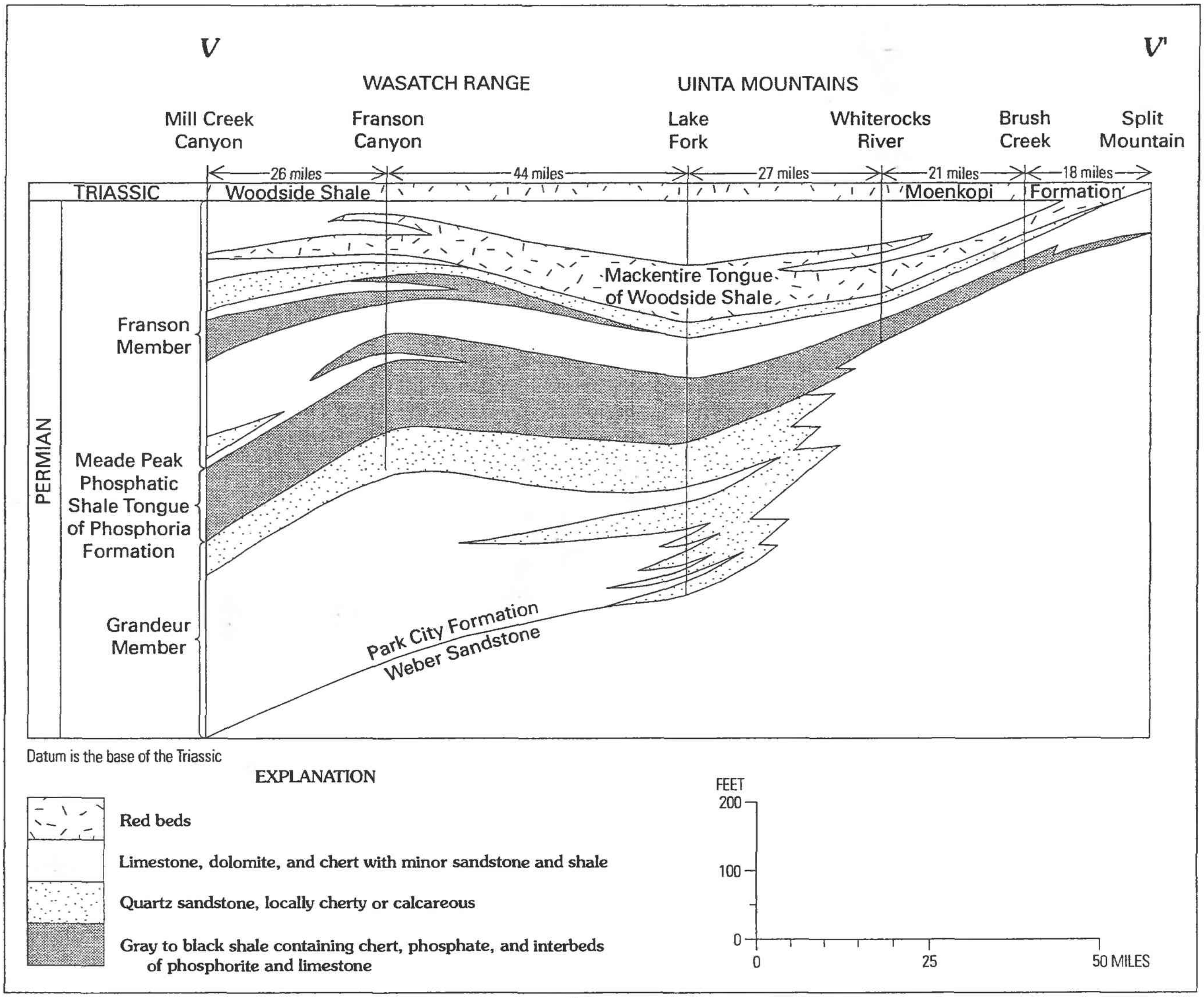



FIGURE 49.—Stratigraphic section showing relations among Permian and Triassic formations in the Uinta Mountains and Wasatch Range, Utah. Modified from McKelvey and others (1959, p. 14), based on reports by Huddle and others (1951), Cheney and others (1953), Untermann and Untermann (1954), and Kinney (1955); location of section shown on plate 17.

Formation and the Ervay Limestone Member. According to Peterson (1984), the Ervay Limestone Member also overlies the Franson Member on the Rock Springs Uplift.

Except for tongues of the Phosphoria Formation and Woodside Shale and the greenish-gray shale facies, the Park City Formation predominantly consists of carbonate rocks and subordinate sandstone layers (fig. 42). The Grandeur Member consists of interbedded limestone, dolomite, and sandstone in thin to massive beds (McKelvey and others, 1959, p. 12–15). The limestone and dolomite layers are yellow, brown, black, and gray, slightly phosphatic, commonly cherty, and fossiliferous. The carbonate beds typically are sandy and grade into sandstone (Huddle and McCann, 1947b; Hansen, 1965b, p. 52; McKelvey and others, 1959, p. 12). Sandstone layers typically are gray, brown, and light yellow, calcareous, cherty, fine to coarse grained, and friable. The basal 5–15 feet of the Grandeur Member in the Wind River Mountains is a conglomerate composed of siltstone, sandstone, quartzite, and chert clasts in a matrix of limestone or sandstone (Keefer and Van Lieu, 1966, p. 44). Carbonate and sandstone layers in the western Uinta Mountains commonly are cavernous and brecciated (Huddle and McCann, 1947b; Huddle and others, 1951).

The Franson Member consists of white, gray, brownish-gray, and yellow limestone, dolomite, and subordinate sandstone in thin to massive beds (McKelvey and others, 1959, p. 15–19). The limestone and dolomite are vuggy, sandy to silty, fine grained to crystalline, and fossiliferous; they commonly contain chert nodules and are locally shaly. Sandstone layers are fine to coarse grained, cherty, and calcareous. Interbeds of dolomitic mudstone are present in some areas.

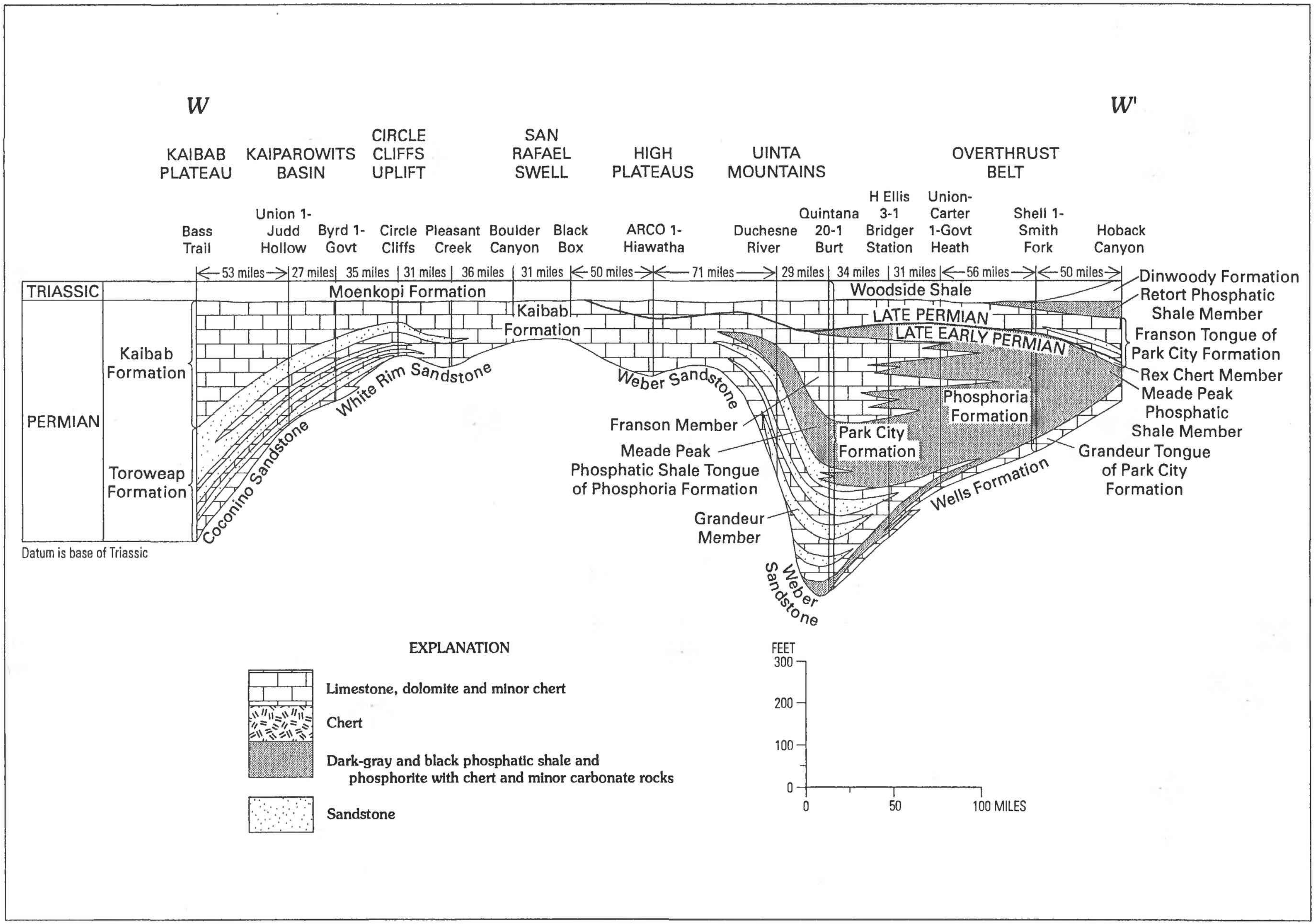



FIGURE 50.—Stratigraphic section showing relations among Permian formations in the western part of the Upper Colorado River Basin, Arizona, Utah, and Wyoming. Compiled from reports by Noble (1922), Gilluly (1929), Huddle and McCann (1947a), Hunt and others (1953), Wanless and others (1955), and Davidson (1967), and from unpublished logs prepared by American Stratigraphic Co.; location of section shown on plate 17.

The Ervay Limestone Member is mostly limestone in the western part of the area and dolomite in the eastern part (McKelvey and others, 1959, p. 19–20). It grades southward into interbedded chert, shale, sandstone, and carbonate rocks of the Tosi Chert Tongue of the Phosphoria Formation. It grades westward into sandstone and chert of the Shedhorn Sandstone (a facies equivalent to the Park City, Phosphoria, and Goose Egg Formations that terminates in the northern Gros Ventre Range, north of the UCRB).

The Park City Formation grades into the Phosphoria Formation in the western and northern Green River Basin, as shale and chert intervals progressively predominate over carbonate and sandstone intervals (fig. 50). The Phosphoria Formation in the study area (fig. 41) consists of the Grandeur Tongue of the Park City Formation, lower chert member, Meade Peak Phosphatic Shale Member, Franson Tongue of the Park City Formation, Rex Chert Member, Retort Phosphatic Shale Member, and Tosi Chert Member (McKelvey and others, 1959, p. 20–31). The Grandeur and Franson Tongues are thinner than but otherwise similar to the Grandeur and Franson Members of the Park City Formation. The lower chert member typically consists of chert with subordinate amounts of carbonate rocks and mudstone. The Meade Peak Phosphatic Shale Member typically is composed of fissile, dark-gray, black, and brown phosphatic to limy mudstone with brown and gray, pelletal, oolitic, and nodular phosphorite, chert, and dark-gray and black, cherty and phosphatic carbonate rocks. South and east of the Overthrust Belt in Wyoming, the Meade Peak Phosphatic Shale Member gains carbonate and chert layers as it grades into the Grandeur and Franson Tongues of the Park City Formation. The Rex Chert Member, which extends no farther east than the western part of the Overthrust Belt, consists of black, gray, and white chert, carbonate rocks, and mudstone. At its eastern limit, the Rex Chert Member grades laterally into the Franson Tongue and Retort Phosphatic Shale Member. The Retort Phosphatic Shale Member is similar to the Meade Peak Shale Member but contains a greater proportion of shale to dolomite and phosphorite (McKelvey and others, 1959, p. 30). The Tosi Chert Member predominantly consists of columnar chert, but interbeds of dark-gray mudstone, sandstone, carbonate rocks, and phosphorite transitional into the Retort Phosphatic Shale Member and Shedhorn Sandstone also are present.

At the southern end of the Uinta Basin, the Meade Peak Phosphatic Shale Tongue of the Phosphoria Formation pinches out, making distinction impossible between the Grandeur and Franson Members of the Park City Formation (fig. 50). The undifferentiated Park City Formation consists of cherty dolomite and limestone with a few shale interbeds. In the San Rafael Swell, equivalent strata are assigned to the Kaibab Formation.

From the San Rafael Swell south to the Kaiparowits Basin, a sequence of interbedded light-yellow, white, gray, and tan sandstone, sandy limestone and dolomite, shale, anhydrite, and gypsum occurs between rocks typical of the White Rim Sandstone and Kaibab Formation. Geologists working in the area, including Gilluly (1929), Gregory and Moore (1931), Baker (1946), Hunt and others (1953), Smith and others (1963), and Davidson (1967), alternately have assigned these rocks to either the Coconino (White Rim) Sandstone or the Kaibab Limestone (Formation). In the Kaibab Plateau, rocks of similar mixed carbonate-clastic lithology occupying the same stratigraphic position are assigned to the Toroweap Formation (McKee, 1969, p. 39). In the northern Kaibab Plateau and Lees Ferry area, for example, the Toroweap Formation consists of laterally discontinuous layers of red, reddish-brown, tan, white,

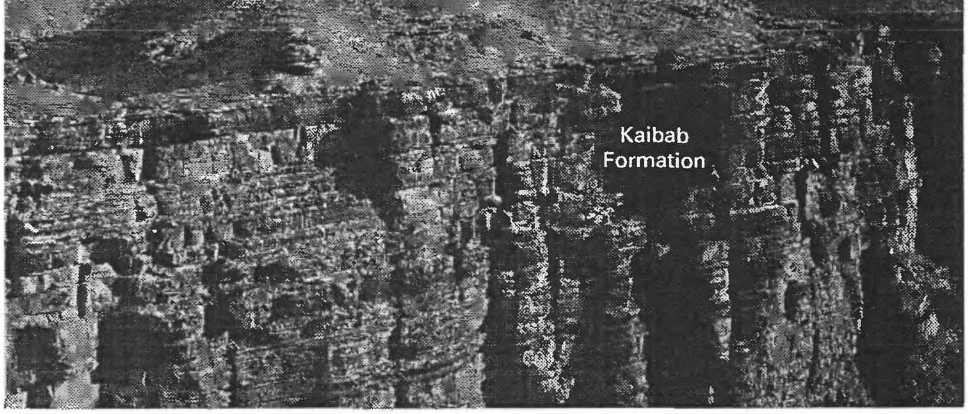



FIGURE 51.—Permian Kaibab Formation in Marble Canyon, Ariz., a regional discharge area for aquifers in the Paleozoic rocks of the Upper Colorado River Basin.

and light-yellow, fine- to medium-grained, friable to limy sandstone, cherty limestone, and silty mudstone (Gregory and Moore, 1931, p. 39; Phoenix, 1963, p. 12). Following Heylmun (1958), the rocks of disputed nomenclature in this report are assigned to the Toroweap Formation.

The Kaibab Formation (fig. 51) ranges from mostly limestone and dolomite in uplifted areas to mostly dolomite in structural basins. In the San Rafael Swell, the formation consists of limestone with sandy layers that grade laterally into limy sandstone (Gilluly, 1929, p. 82; Baker, 1946, p. 50–51; Hunt and others, 1953, p. 46–47; Welsh and others, 1979, p. 145). In the Capitol Reef Fold and Fault Belt and Circle Cliffs Uplift, carbonate layers similarly grade laterally into sandstone layers. However, many of the limestone beds have been dolomitized, retaining a relict oolitic texture (Gregory and Moore, 1931, p. 42; Smith and others, 1963, p. 9; Davidson, 1967, p. 13–14). Lenses of gray shale occur in the Capitol Reef Fold and Fault Belt, and partings of green, glauconitic sandstone occur in the Circle Cliffs Uplift. From the northern Kaibab Plateau to the Lees Ferry area, the formation changes westward from a sandy dolomitic limestone with thin shale interbeds in the upper part to a crystalline limestone with sandstone and shale layers near the base and top (Gregory and Moore, 1931, p. 39; Phoenix, 1963, p. 13). In most uplifted areas, the Kaibab Formation is characterized by asphalt-filled vugs. East of the San Rafael Swell, Capitol Reef Fold and Fault Belt, Circle Cliffs Uplift, and Kaibab Plateau—in the Henry Mountains and Kaiparowits Basins—the formation mostly consists of dolomite (Heylmun, 1958, p. 1800; Welsh and others, 1979, p. 146). Throughout its extent, the Kaibab Formation is characterized by bedding ranging from inches to 10 ft in thickness, a vuggy appearance, colors of gray, beige, tan, light yellow, and white, and inclusions of chert (with calcite and quartz in some areas) as layers, fragments, nodules, and geodes.

### UPPER CONTACTS

Component geologic units in the Park City–State Bridge zone are overlain conformably to unconformably by Triassic formations composed mostly of shale. The contact between the Phosphoria and Dinwoody Formations in the Overthrust Belt is an unconformity (Wanless and others, 1955, p. 39). The Park City Formation is overlain unconformably by the Dinwoody Formation on the north slope of the Uinta Mountains (Hansen, 1965b, p. 64) but conformably in the Wind River Mountains (Keefer and Van Lieu, 1966, p. 47). On the south slope of the Uinta Mountains, the Woodside Shale and Moenkopi Formation conformably overlie and intertongue with the Park City Formation (McKelvey and others, 1959, p. 19; Schell and Yochelson, 1966, p. 67). Permian and Triassic members of the State Bridge Formation were deposited without an intervening erosional hiatus and, thus, are conformable (Freeman, 1971, p. 7). Permian and Triassic members of the Goose Egg Formation, however, are separated by an erosional hiatus (Peterson, 1984, p. 28). The Kaibab Formation throughout its depositional area is overlain unconformably by the Moenkopi Formation. Except for channels as much as 25 ft deep in the Lees Ferry area, this unconformity is barely discernible in the Kaibab Plateau–Marble Platform region (Gregory and Moore, 1931, p. 45; Phoenix, 1963, p. 13; McKee, 1969, p. 47). From the Circle Cliffs Uplift to the San Rafael Swell, however, the erosional surface on top of the Kaibab Formation is hummocky, contains channels as much as 100 ft deep and, in places, completely cuts out the underlying unit (Gilluly, 1929, p. 82; Baker, 1946, p. 51; Davidson, 1967, p. 13–15).

## SUMMARY AND CONCLUSIONS

The Upper Colorado River Basin (UCRB) is situated in parts of four physiographic provinces—the Middle Rocky Mountains, Wyoming Basin, Southern Rocky Mountains, and Colorado Plateaus. Within each physiographic province, numerous uplifts and basins occur. Thrust faults and high-angle normal and reverse faults are associated with many of the uplifts. Tectonic activity has occurred repeatedly since the Precambrian.

Formations comprising all Paleozoic systems except the Silurian are present in the UCRB. The Paleozoic rocks were deposited during five major marine incursions. Thicknesses range from 0 in the interiors of most uplifts to about 18,000 ft in the Elk Mountains of Colorado. The Paleozoic rocks are at or near land surface on the flanks of uplifts but are 2,500–27,000 ft deep in structural basins.

The Paleozoic rocks are underlain by Precambrian igneous, metamorphic, and sedimentary rocks. Cambrian to Mississippian formations consist of limestone and dolomite with subordinate sandstone, quartzite, and shale. Pennsylvanian and Permian formations consist of sandstone, conglomerate, and shale with subordinate carbonate rocks and locally thick intervals of bedded evaporites. The Paleozoic rocks are overlain in most areas by Triassic formations predominantly composed of shale. In a few small areas, Jurassic sandstone or Tertiary sandstone and shale overlie the Paleozoic rocks.

The Paleozoic rocks are divisible on the basis of lithologic and hydrologic properties into 11 hydrogeologic units. The basal unit, the Flathead aquifer, includes the Flathead Sandstone, lower part of the Lodore Formation, Sawatch Quartzite, Ignacio Quartzite, Tapeats Sandstone, Tintic Quartzite, and unnamed equivalents. Component geologic units decrease in age from Early and Middle Cambrian on the west to Middle and Late Cambrian on the east. The thickness of the Flathead aquifer ranges from 0 to 800 ft. Regionally, almost the entire thickness of the aquifer consists of quartzite and friable to quartzitic sandstone. A basal conglomerate interval, a few feet to more than 50 ft thick, is present throughout most of the area, and the sandstone locally is conglomeratic. Carbonate rocks comprise 5–20 percent of the unit toward depositional centers, particularly in northwestern Colorado, where the sandstone and quartzite commonly are dolomitic. Shale layers occur with increasing frequency toward the upper part of the unit and can be nearly as abundant as sandstone and quartzite layers on the southern and eastern edges of the region, where Cambrian sandstone and shale formations are gradational. Formations in the Flathead aquifer are underlain with slight to substantial unconformity by Precambrian rocks and are overlain in most areas conformably to gradationally by other Cambrian formations. In some areas, such as the eastern Great Divide Basin, the eastern Uinta Mountains, and the Sawatch Range, component geologic units are overlain unconformably by formations of Cambrian to Mississippian age.

Overlying the Flathead aquifer in most areas is the Gros Ventre confining unit. The Gros Ventre confining unit includes the Gros Ventre Formation, upper part of the Lodore Formation, Bright Angel Shale, Ophir Shale, and unnamed equivalents. Component geologic units decrease in age eastward from Early and Middle Cambrian to Late Cambrian. The thickness of the Gros Ventre confining unit ranges from 0 to 1,100 ft. Regionally, the Gros Ventre confining unit is composed of claystone, siltstone, and sandy shale with subordinate interbeds of sandstone, limestone, and dolomite. The sandstone commonly is micaceous and glauconitic, but quartzitic layers are present, particularly near the base and margins where Cambrian shale formations grade into sandstone formations of the underlying Flathead aquifer. At the margins of depositional centers, the sandstone and shale tend to be present in subequal amounts. Carbonate rocks progressively increase in abundance toward depositional centers, where they can be nearly as abundant as shale layers. In the northern UCRB, the Gros Ventre confining unit is overlain unconformably in most areas by formations of Cambrian to Mississippian age, but at the eastern end of the Wind River Mountains, the Gros Ventre Formation grades into the Cambrian Gallatin Limestone. In the western Uinta Mountains and areas to the south and east in Utah, Colorado, and Arizona, component geologic units generally are overlain conformably to gradationally by other Cambrian formations.

The third hydrogeologic unit in the Paleozoic sequence, the Bighorn aquifer, includes the Gallatin Limestone, Dotsero Formation, Peerless Formation, Muav Limestone, Maxfield Limestone, Lynch Dolomite, Manitou Dolomite, Harding Sandstone, Fremont Limestone, Bighorn Dolomite, and unnamed equivalents. Component geologic units generally are considered to be Middle Cambrian to Late Ordovician in age. The thickness of the Bighorn aquifer ranges from 0 to 3,000 ft. Regionally, the aquifer consists of limestone and dolomite with subordinate shale layers and generally less than 5 percent sandstone layers. Cambrian carbonate rocks within the Bighorn aquifer typically are glauconitic and oolitic and contain flat-pebble or edgewise conglomerate layers; in the Four Corners area, the Cambrian rocks are shaly. Ordovician carbonate rocks within the Bighorn aquifer can be granular, crystalline, or fine grained, and the Manitou Dolomite tends to be siliceous. Shale and sandstone layers comprise less than 20 percent of the Bighorn aquifer and are most abundant toward the bottom and margins of the unit, where component geologic units grade into other Cambrian formations. In all areas, the upper surface of geologic units comprising the Bighorn aquifer is an unconformity upon which Devonian and Mississippian rocks were deposited.

The next hydrogeologic unit in the Paleozoic sequence, the Elbert-Parting confining unit, includes the Darby, Parting, Elbert, and Temple Butte Formations, and the Cottonwood Canyon Member of the Lodgepole and Madison Limestones. Component geologic units are Early Devonian to Early Mississippian in Wyoming and Late Devonian in age elsewhere. The thickness of the Elbert-Parting confining unit ranges from 0 to 700 ft. Regionally, the Elbert-Parting confining unit is characterized by highly variable proportions of limestone, dolomite, sandstone, quartzite, shale, and anhydrite. Generally, the Darby, Elbert, and Temple Butte Formations contain increasing thicknesses of carbonate rocks and decreasing thicknesses of clastic rocks westward across the UCRB, and the Parting Formation becomes more carbonaceous toward the center of its depositional basin. In most areas, carbonate rocks comprise at least 50 percent of the confining unit. Shale layers generally comprise at least one-third of the confining unit and locally exceed carbonate layers in abundance. Sandstone and quartzite layers rarely comprise more than one-third of the confining unit, but they predominate on the southeastern edge of the Darby–Cottonwood Canyon depositional basin, on the northeastern edge of the Parting depositional basin, and at the base of the Elbert Formation. Anhydrite layers comprise as much as 10 percent of the Elbert-Parting confining unit in the Overthrust Belt west of Kemmerer, Wyo. Component geologic units in Wyoming and the Grand Canyon area are overlain unconformably by Mississippian carbonates, whereas the Elbert and Parting Formations generally are overlain conformably by formations of Devonian and Mississippian age.

Above the Elbert-Parting confining unit is the Madison aquifer, which is divisible into two lithologically distinct zones, the Redwall-Leadville zone and the Darwin-Humbug zone. The Madison aquifer of the UCRB is an extension of the Madison aquifer of the Northern Great Plains.

The Redwall-Leadville zone includes the Dyer Dolomite, Ouray Limestone, Gilman Sandstone, Leadville Limestone, and Redwall Limestone; the lower part of the Mission Canyon Limestone; and the main bodies of the Lodgepole and Madison Limestones. Component geologic units mostly are Late Devonian to Late Mississippian in age. The thickness of the Redwall-Leadville zone ranges from 0 to 2,500 ft. Limestone, dolomite, and bedded and nodular chert comprise more than 95 percent of the Redwall-Leadville zone, with the proportion of limestone to dolomite decreasing away from uplifted areas. Regional tracing of stratigraphic markers between outcrops and boreholes indicates that limestone beds grade laterally into dolomite beds, such that neither the proportions nor sequence of limestone and dolomite can be used to establish contacts between Devonian and Mississippian formations. Sandstone and shale, concentrated in the interval between Devonian and Mississippian carbonate deposits and at the top of the Mississippian sequence, comprise 5–10 percent of the Redwall-Leadville zone in areas interpreted to have been sites of shallow marine or intermittently subaerial deposition. The upper surface of the Redwall-Leadville zone is an unconformity that progressively truncates older rocks from west to east across the region.

Overlying the Redwall-Leadville zone in and near the Great Divide Basin, the north flank of the Wind River Mountains, the Gros Ventre Range, the Overthrust Belt, the Uinta Mountains, and the Uinta Basin is the Darwin-Humbug zone. The Darwin-Humbug zone includes the Humbug Formation, the Bull Ridge Member of the Madison Limestone, the upper (evaporitic) part of the Mission Canyon Limestone, and the Darwin Sandstone Member of the Amsden Formation. Component geologic units are Early and Late Mississippian in age. The thickness of the Darwin-Humbug zone ranges from 0 to 800 ft. Characteristically, the hydrogeologic unit consists of variable proportions of carbonate rocks, sandstone, shale, gypsum, and solution breccia. Carbonate rocks comprise more than 75 percent of the Darwin-Humbug zone in the centers of depositional areas. Sandstone layers increase in abundance away from depositional centers as carbonate layers decrease. Carbonate layers typically are brecciated, and sandstone layers are brecciated in the western part of the area. Gypsum layers are abundant at the northern end of the Hoback Range in Wyoming. Contacts with Mississippian and Pennsylvanian formations that comprise the overlying Four Corners confining unit generally are conformable.

The Four Corners confining unit is divisible upward into the Belden-Molas and Paradox–Eagle Valley subunits. The Belden-Molas subunit includes the Horseshoe Shale Member of the Amsden Formation, the Doughnut Shale, the Molas, Belden, Watahomigi, and Surprise Canyon Formations, and the lower member of the Hermosa Formation. Component geologic units are Late Mississippian to Middle Pennsylvanian and become younger from west to east across the area. The Belden-Molas subunit consists of as much as 4,300 ft of dark-gray, black, and red shale with subordinate limestone, dolomite, sandstone, and minor evaporite layers. In most areas, shale comprises 50 to more than 75 percent of the Belden-Molas subunit. However, in the Washakie Basin and depositional centers south of the Uinta Mountains and Axial Basin Arch, limestone and dolomite layers can equal or exceed shale layers in abundance and locally comprise more than 75 percent of the subunit. Sandstone layers comprise about one-third of the Belden-Molas subunit where it thins on the flanks of uplifted areas. Contacts with overlying geologic units of Late Mississippian to Pennsylvanian age generally are conformable to gradational.

In most areas, the Belden-Molas subunit is overlain by the Paradox–Eagle Valley subunit, which includes the Moffat Trail Limestone Member of the Amsden Formation, the Round Valley Limestone, the Eagle Valley Evaporite, the Paradox Member of the Hermosa Formation, and the Manakacha Formation. Component geologic units are Late Mississippian to Middle Pennsylvanian in age and become younger in a south-southeasterly direction. The thickness of the Paradox–Eagle Valley subunit ranges from 0 to more than 9,000 ft, except in small areas of the Paradox Basin where salt diapirs as much as 15,000 ft thick are present. Regionally, the Paradox–Eagle Valley subunit consists of varying proportions of limestone, dolomite, shale, sandstone, anhydrite (or gypsum), and halite. Anhydrite, halite, shale, and minor carbonate rocks are the dominant lithologies in and near the Paradox and Eagle Basins. This hypersaline facies grades outward into a penesaline facies composed of limestone, dolomite, shale, anhydrite, and sandstone, which, in turn, grades into a marine-shelf facies composed of limestone and dolomite with subordinate shale and minor sandstone. The marine-shelf facies predominates from the Uinta and Sand Wash Basins to the northern edge of the study area. On the southern edge of the study area a facies consisting of red shale and sandstone, subordinate carbonate rocks, and minor anhydrite predominates. Contacts between component geologic units and formations in the overlying Canyonlands aquifer generally are gradational to disconformable.

The Canyonlands aquifer, in ascending order, consists of the Cutler-Maroon, Weber–De Chelly, and Park City–State Bridge zones. Each of these zones has distinct lithologic and hydrologic properties.

The Cutler-Maroon zone of the Canyonlands aquifer includes the Ranchester Limestone Member of the Amsden Formation, upper member of the Hermosa Formation, Rico Formation, Gothic Formation, Minturn Formation, Morgan Formation, the main body of the Maroon Formation, Cutler Formation, Halgaito Shale, Elephant Canyon Formation, Cedar Mesa Sandstone, Organ Rock Shale, Supai Formation, Wescogame Formation, Esplanade Sandstone, and Hermit Shale. Component geologic units are Early Pennsylvanian to Late Permian and become younger in a south-southwesterly direction. Regionally, the Cutler-Maroon zone consists of as much as 16,500 ft of sandstone, conglomerate, shale, limestone, dolomite, and gypsum-anhydrite. Sandstone and conglomerate generally make up 50 to more than 75 percent of the Cutler-Maroon zone within and adjacent to uplifted areas on the east, south, and west. The sandstone in these areas predominantly is red, arkosic, micaceous, coarse grained, and friable; most of the interbeds are siltstone or mudstone; carbonate intervals are thin and sparsely distributed. Away from these uplifts, the rocks become predominantly gray, green, tan, and pink; arkosic sandstone layers become finer grained, more indurated, and less numerous; quartz sandstone intervals thicken and predominate over arkosic intervals; siltstone and mudstone intervals thicken and equal or exceed sandstone in abundance; limestone and dolomite intervals thicken and comprise as much as 45 percent of the rock material; thin gypsum or anyhdrite beds occur locally. In northern and central parts of the study area, the Cutler-Maroon zone consists of limestone and dolomite with subordinate shale interbeds, generally less than 25 percent sandstone interbeds, and, locally, minor interbeds of gypsum or anhydrite. Contacts between component geologic units and overlying Pennsylvanian and Permian rocks generally are conformable to gradational, but local unconformities exist. In southeastern Utah east of the Monument Upwarp and in western Colorado south of the Piceance Basin, component geologic units of the Cutler-Maroon zone generally are the youngest Paleozoic rocks and are overlain conformably to unconformably by Mesozoic rocks.

The middle division of the Canyonlands aquifer, the Weber–De Chelly zone, includes the Wells Formation, Tensleep Sandstone, Weber Sandstone, White Rim Sandstone, Coconino Sandstone, De Chelly Sandstone, and the Schoolhouse and Fryingpan Members of the Maroon Formation. Component geologic units decrease in age southward from Middle and Late Pennsylvanian to Late Permian. Over most of the study area, the Weber–De Chelly zone consists of as much as 4,000 ft of light-colored, quartz sandstone with generally thin interbeds of siltstone, mudstone, limestone, dolomite, and anhydrite that comprise no more than 10 percent of the thickness of the zone. However, carbonate rocks constitute 10–30 percent of the Weber–De Chelly zone on the western edge of the UCRB, from the Wasatch Plateau north to the Overthrust Belt, and in parts of the Green River and Great Divide Basins. Shale layers constitute as much as 30 percent of the Weber–De Chelly zone near its eastern and western depositional edges in Colorado, Utah, and New Mexico. Contacts between component geologic units and overlying formations of Permian and Triassic age are gradational to unconformable.

The uppermost zone within the Canyonlands aquifer, the Park City–State Bridge zone, is present only in the northern and western parts of the UCRB. It includes the Kaibab, Toroweap, Park City, and Phosphoria Formations and the lower (Permian) parts of the Goose Egg and State Bridge Formations. Component geologic units decrease in age from Early to Late Permian southward. The thickness of the Park City–State Bridge zone ranges from 0 to 800 ft. In Wyoming and northwestern Colorado, a facies consisting of red shale with subordinate sandstone, gypsum-anhydrite, limestone, and dolomite grades westward into a depositional sequence consisting of varying proportions of limestone, dolomite, greenish-gray to black shale, phosphatic shale, phosphorite, chert, and sandstone. To the south, in Utah and Arizona, the shale and phosphatic intervals pinch out, and gypsum-anhydrite layers locally comprise 5–30 percent of the Park City–State Bridge zone. Component geologic units in the Park City–State Bridge zone are overlain conformably to unconformably by Triassic formations.

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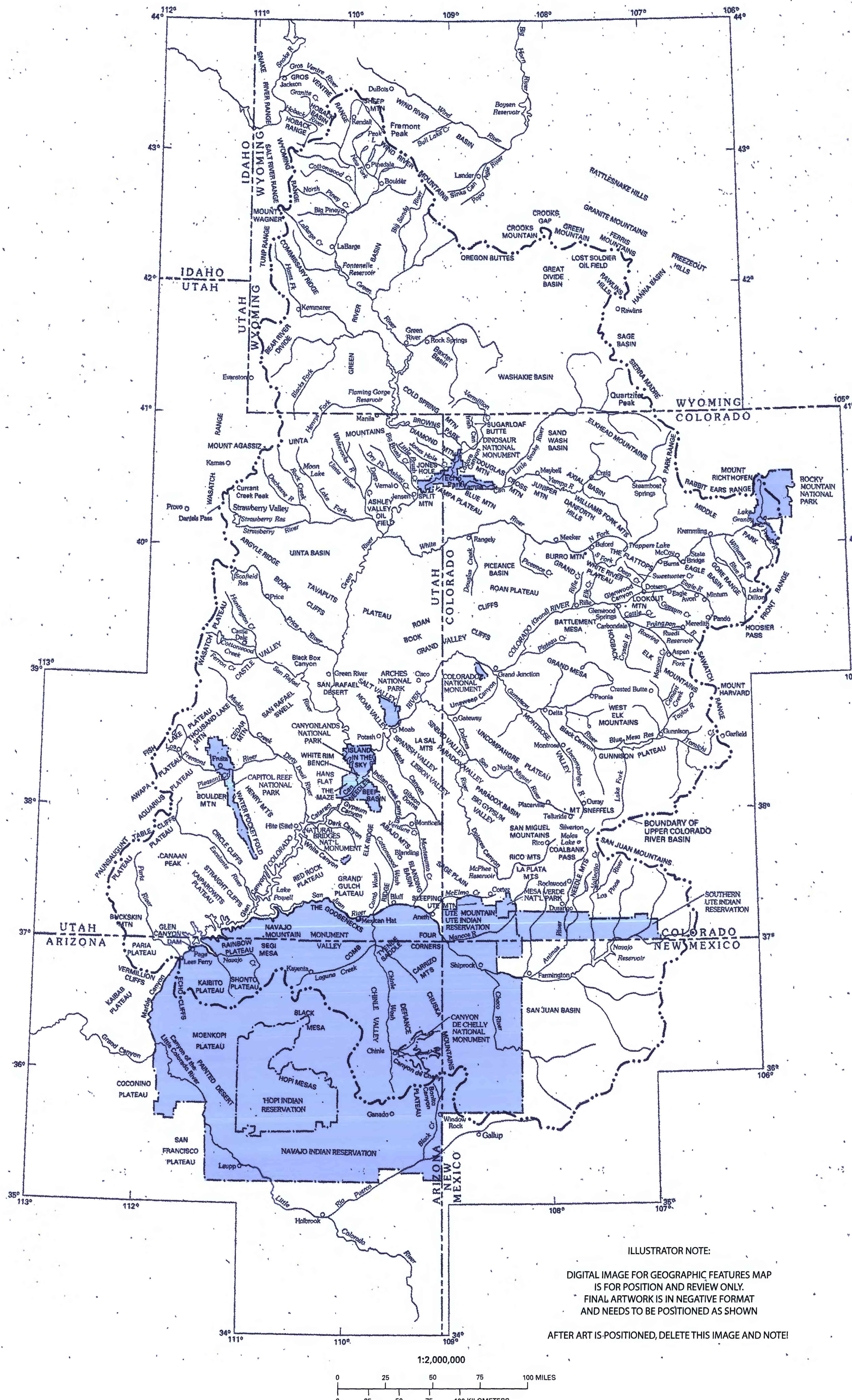


ILLUSTRATOR NOTE:

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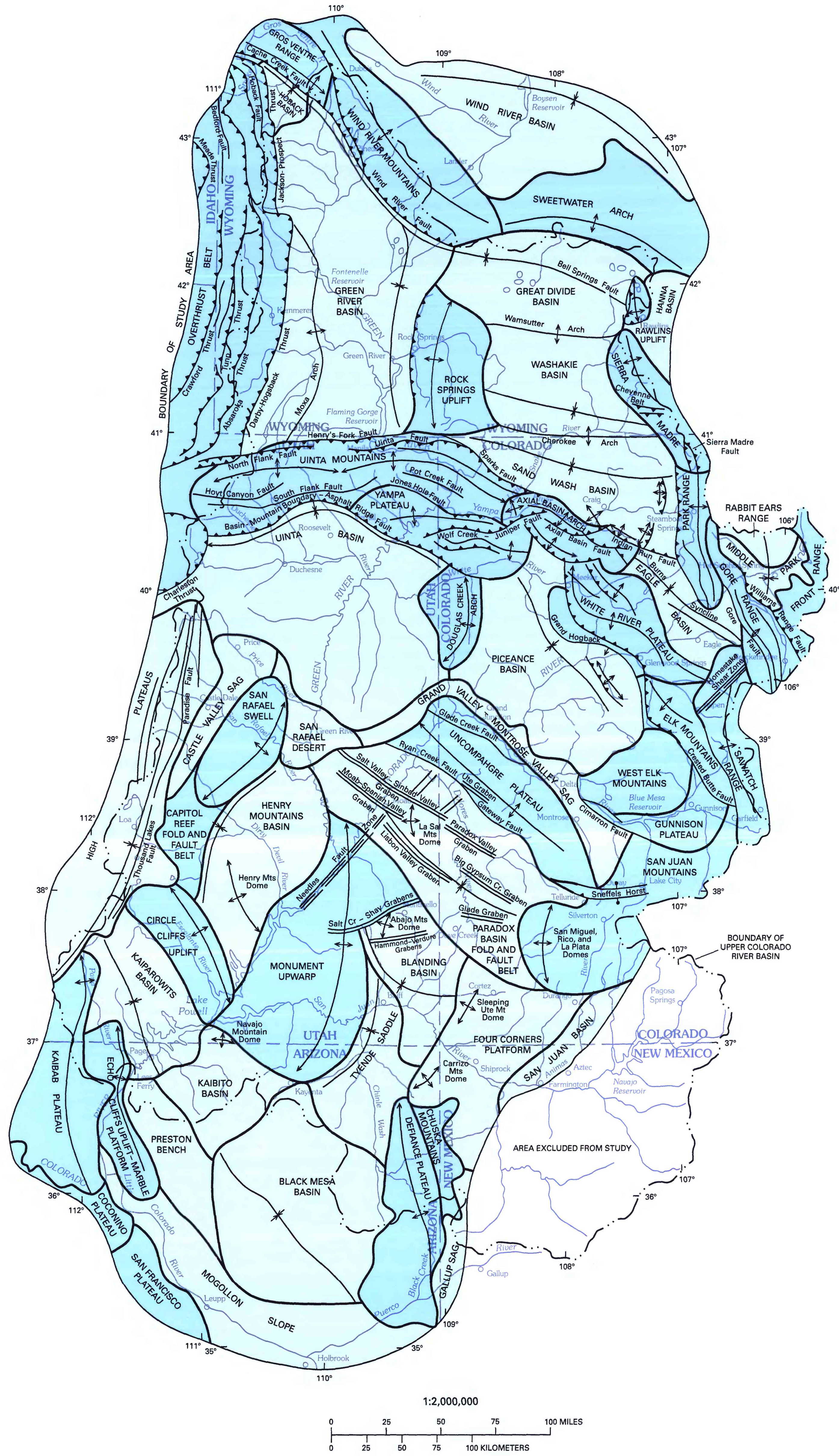
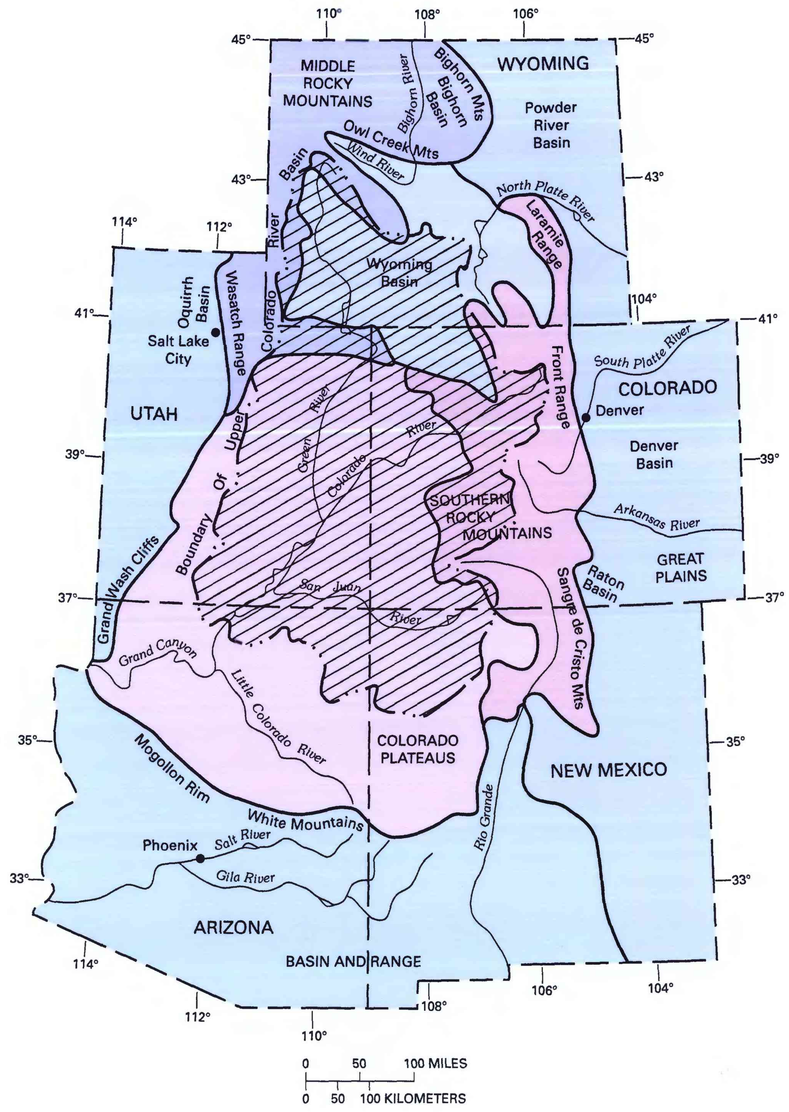
GEOGRAPHIC FEATURES




STRUCTURAL FEATURES




INDEX MAP SHOWING LOCATION OF UPPER COLORADO RIVER BASIN WITH RESPECT TO PHYSIOGRAPHIC PROVINCES

**EXPLANATION**

- Anticline
- Syncline
- Plunging anticline
- Dome or doubly plunging anticline
- Boundary of structural feature, shown only where boundary does not coincide with a fault
- Structural basin
- Uplift
- Fault, generally high angle
- Fault zone
- Graben
- Horst
- Thrust fault, teeth on upper plate

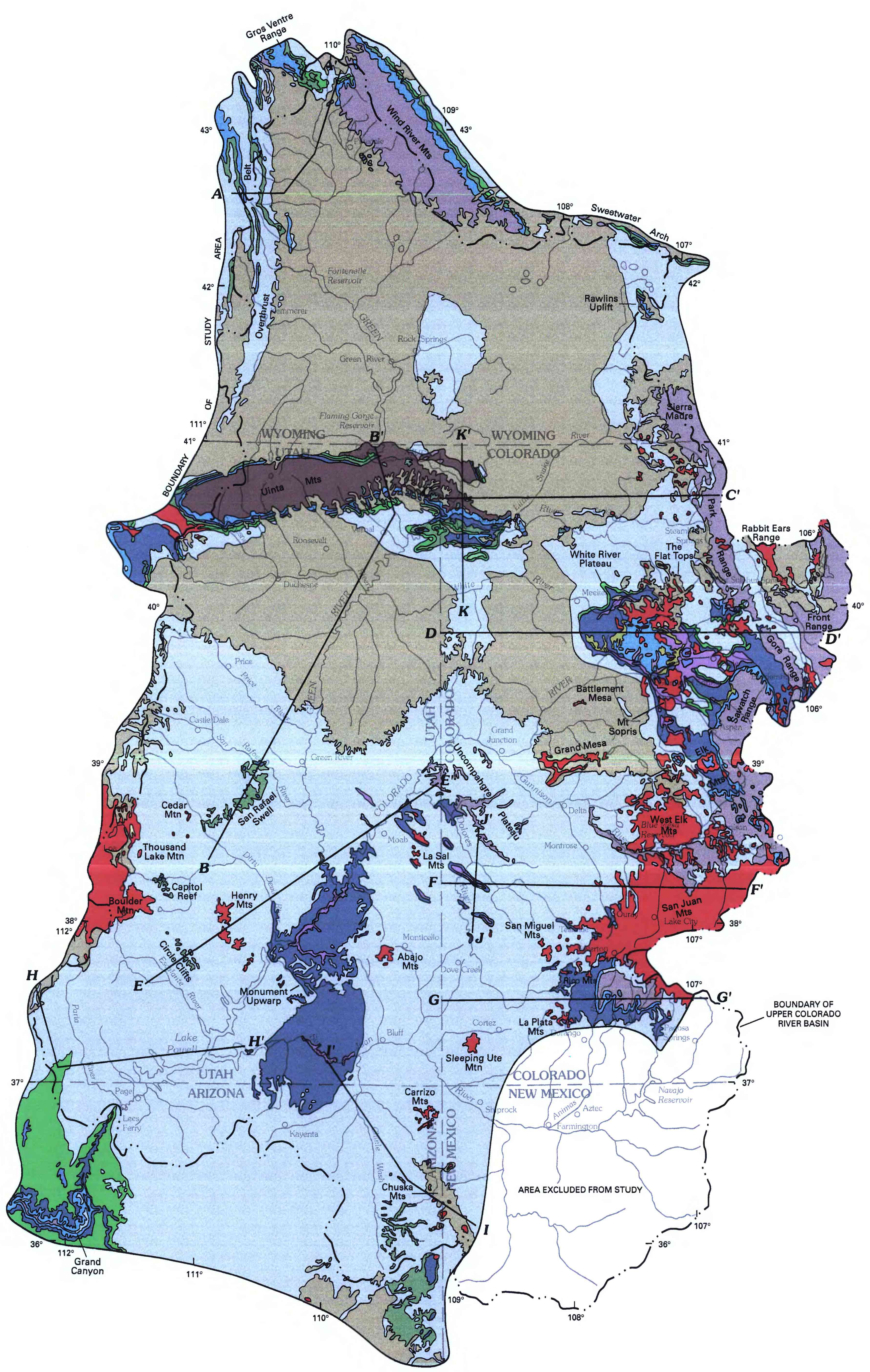
Map of structural features modified from maps by Grose (1972), Baars (1983), and Taylor and others (1983), based mainly on Williams (1964), Roberts and others (1965), Ritzma (1969), Williams and Hackman (1971), Haynes and others (1972), Cashion (1973), Hackman and Wyant (1973), Tweto (1976), Tweto and others (1976, 1978), Snyder (1980a, 1980b, 1980c), Hansen (1986a), Stone (1986), Blackstone and DeBruin (1987), and Lageson (1987) and on isopach and lithofacies maps prepared for this report.

Map of physiographic provinces modified from Howard and others (1972).

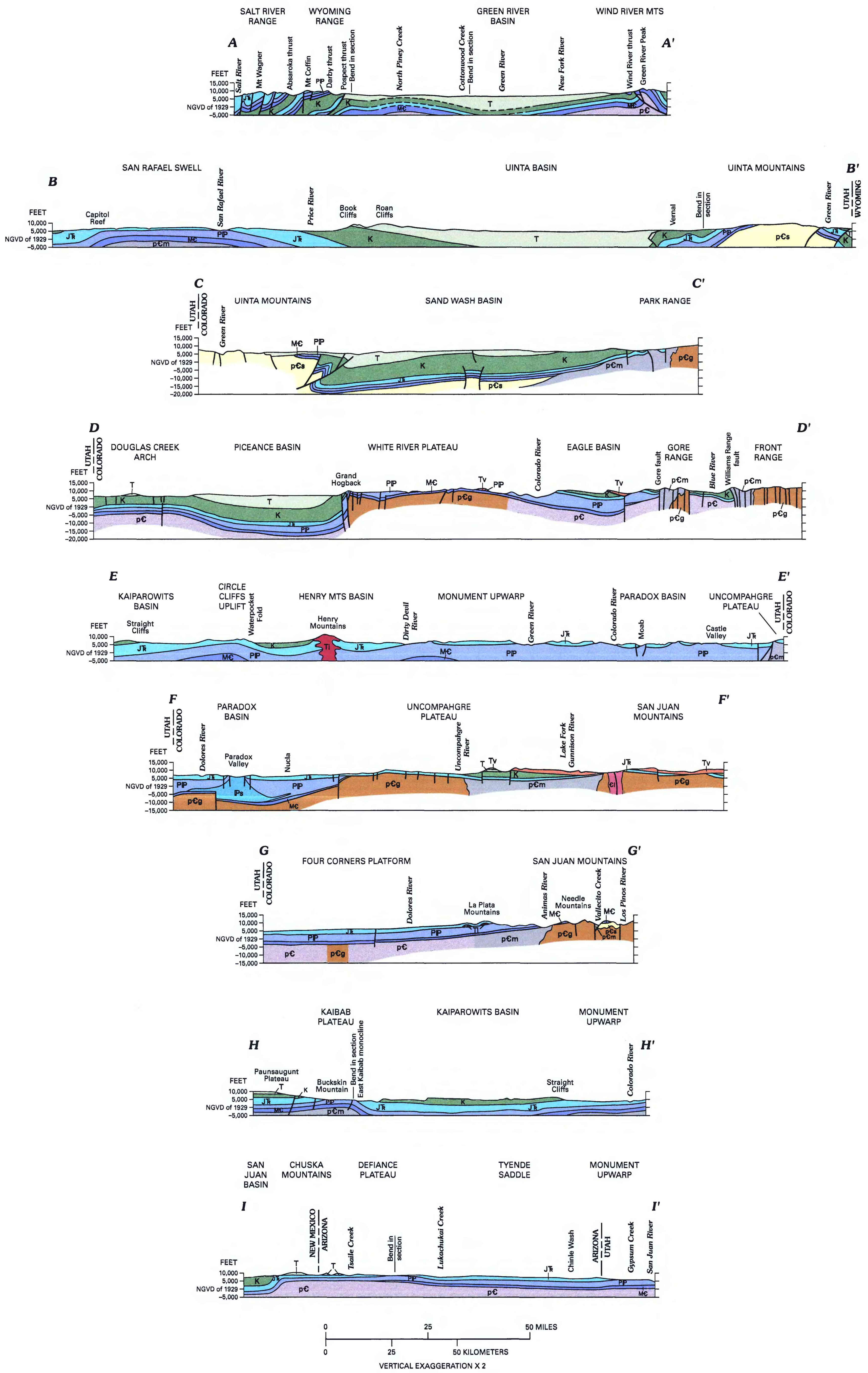
Base from U.S. Geological Survey
U.S. base map, 1:2,500,000

# GEOGRAPHIC AND STRUCTURAL FEATURES OF THE UPPER COLORADO RIVER BASIN AND VICINITY IN ARIZONA, COLORADO, NEW MEXICO, UTAH, AND WYOMING

By
Arthur L. Geldon
2002




GEOLOGY




GEOLOGIC CROSS SECTIONS

## EXPLANATION

**Geologic Map Units—Quaternary alluvium and colluvium not shown**

- **Tertiary sedimentary rocks**
- **Tertiary igneous rocks**
- **Mesozoic sedimentary rocks**
- **Permian formations composed of shale, sandstone, chert, carbonate rocks, evaporites, and phosphorite. Not shown generally in Overthrust Belt because of scale**
- **Permian and Pennsylvanian quartz sandstone. Includes minor interbedded carbonate rocks and shale. Not shown in White River Plateau, Elk Mountains, Monument Upwarp, and Grand Canyon area because of scale**
- **Permian and Pennsylvanian formations composed of sandstone, shale, and interbedded carbonate rocks. Not shown in Wyoming, except in Rawlins Uplift, because of scale**
- **Eagle Valley Evaporite and Paradox Member of Hermosa Formation**—Bedded evaporites of Pennsylvanian age. Shown only where prominent outcrops are present
- **Belden and Molas Formations**—Black shale with interbedded carbonate rocks and minor gypsum overlying a thin red shale regolith. Formations are mostly Pennsylvanian in age. Shown only where Eagle Valley Evaporite crops out in northwestern Colorado
- **Mississippian, Devonian, Ordovician, and Cambrian formations**—Composed of limestone and dolomite with interbedded quartzite, sandstone, and shale
- **Precambrian sedimentary rocks and slightly metamorphosed sedimentary rocks**
- **Precambrian igneous and metamorphic rocks**

**Geologic Cross Section Units**

**Sedimentary rocks**

- Mz — Mesozoic sedimentary rocks
- T — Tertiary sedimentary rocks
- K — Cretaceous sedimentary rocks
- JŦ — Jurassic and Triassic sedimentary rocks
- PP — Permian and Pennsylvanian sedimentary rocks
- Ps — Pennsylvanian Paradox Member of Hermosa Formation
- M€ — Mississippian, Devonian, Ordovician, and Cambrian sedimentary rocks
- p€s — Precambrian sedimentary rocks

**Igneous rocks**

- Tv — Tertiary volcanic rocks
- Ti — Tertiary intrusive rocks
- €i — Cambrian intrusive rocks
- p€g — Precambrian granitic rocks
- p€m — Precambrian metamorphic rocks
- p€ — Precambrian igneous and metamorphic rocks

**Line Symbols**

- **Fault**—Barbs (in figures 5 and 6) indicate relative directions of movement
- **Geologic contact**—Dashed where approximately located
- *A*——*A'* **Location of geologic cross section shown on plate 2 and figures 5 and 6**

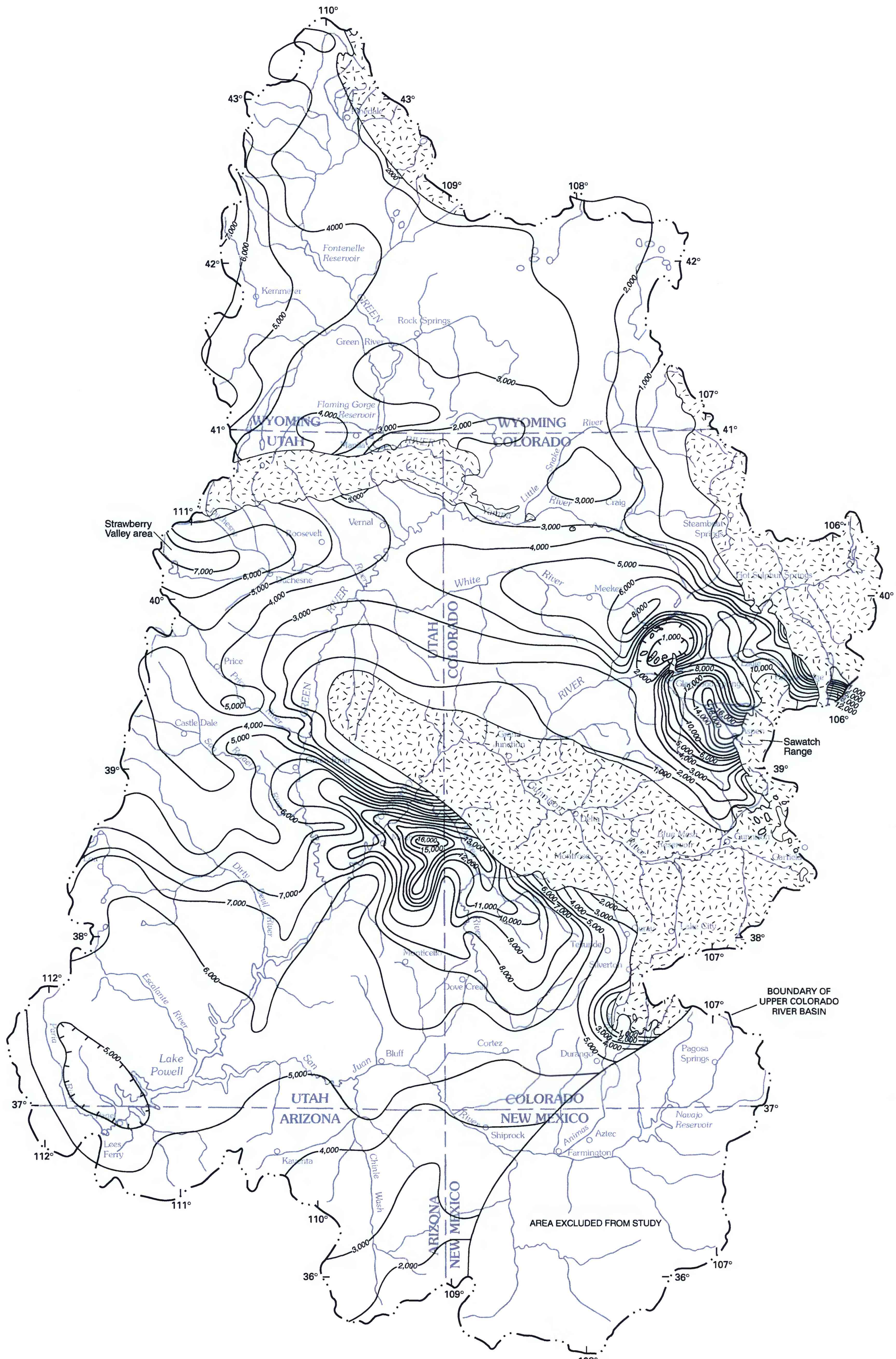
The geologic map was compiled from 1:500,000-scale State geologic maps prepared by Dane and Bachman (1965), Wilson and others (1969), Tweto (1979), Hintze (1980), and Love and Christiansen (1985). Geologic cross section *A–A'* was prepared from reports by Richmond (1945), Rubey (1973), and Royse and others (1975), and unpublished borehole logs; sections *B–B'* through *H–H'* were modified from Hintze (1980) and Tweto (1980b); section *I–I'* was prepared mainly from Harshbarger and Repenning (1954), O'Sullivan and Beikman (1963), Haynes and others (1972), and unpublished borehole logs. The intersection points of cross sections are not shown here and elsewhere in this report. The sections are taken from the work of other authors and thus represent different interpretations and generalizations. Showing the intersection points could give the misleading impression that errors were made in drawing one or both of the intersecting sections.

Base from U.S. Geological Survey
U.S. base map, 1:2,500,000

# GENERALIZED GEOLOGY OF THE UPPER COLORADO RIVER BASIN AND VICINITY IN ARIZONA, COLORADO, NEW MEXICO, UTAH, AND WYOMING

By
Arthur L. Geldon
2002

Geldon, A.L., 2002, Geology of Paleozoic rocks in the Upper Colorado River Basin in Arizona, Colorado, New Mexico, Utah, and Wyoming, excluding the San Juan Basin

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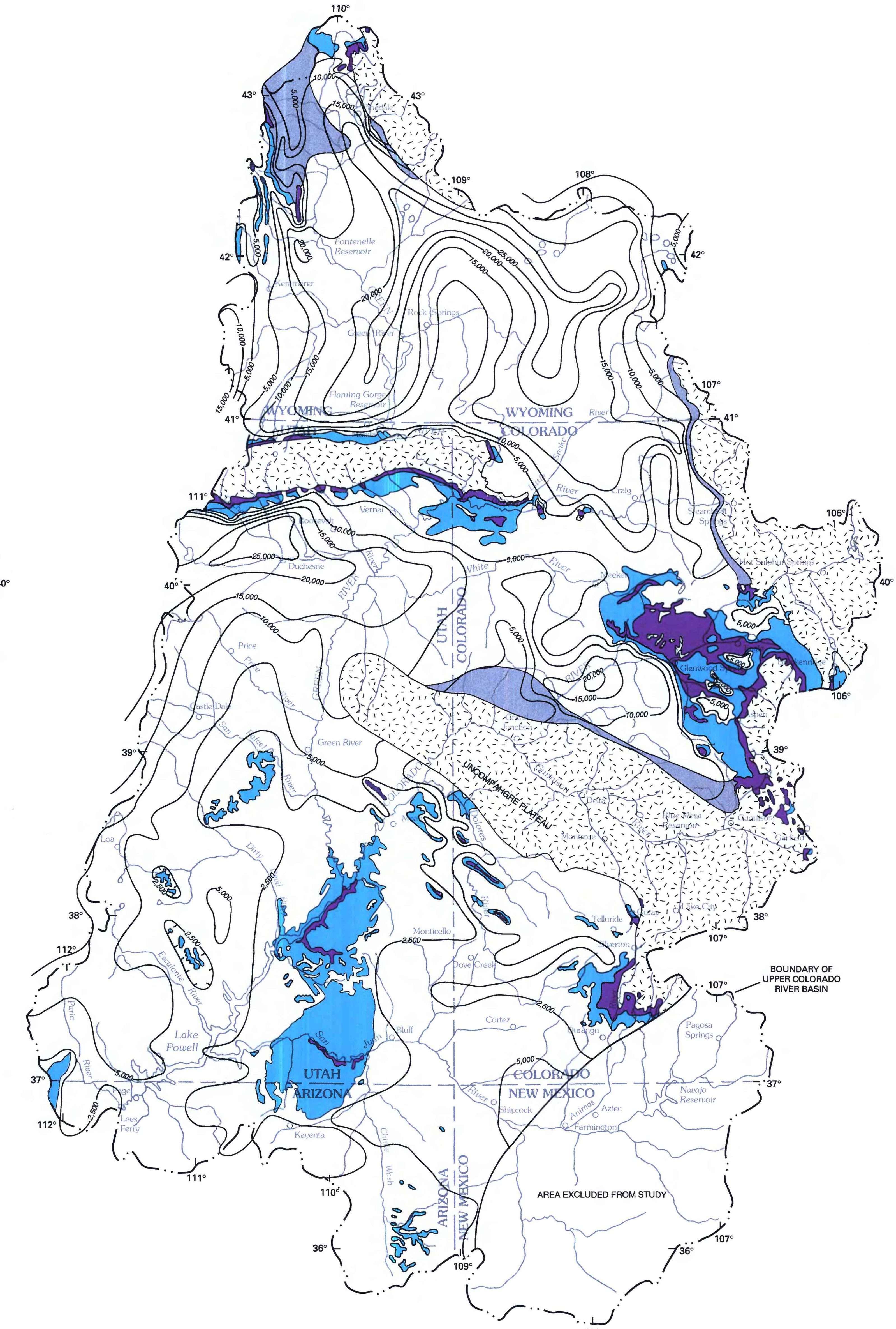
THICKNESS OF PALEOZOIC ROCKS

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DEPTH TO TOP OF PALEOZOIC ROCKS

## EXPLANATION

Area where the Paleozoic rocks crop out (generalized). Blue indicates Canyonlands aquifer, purple indicates geologic units below Canyonlands aquifer

Area where the Paleozoic rocks are missing because of erosion or nondeposition or are thrust beneath Precambrian rocks

Area where the top of the Paleozoic rocks is below the Canyonlands aquifer (see table 1 for component geologic units)

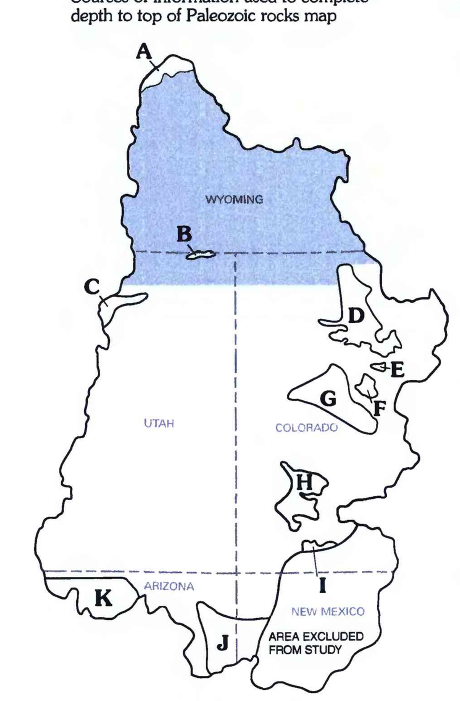
### Thickness of Paleozoic rocks

—1,000— **Line of equal thickness of Paleozoic rocks, excluding Paleozoic rocks above Charleston Thrust Fault in Strawberry Valley area, Utah**—Interval generally is 1,000 feet; 2,000 feet in northwestern Colorado near Sawatch Range because of abrupt thickness changes

### Depth to top of Paleozoic rocks

—5,000— **Line of equal depth to top of Paleozoic rocks**—Interval north of Uncompahgre Plateau is 5,000 feet; interval to south is 2,500 feet

Sources of information used to complete depth to top of Paleozoic rocks map




Except where noted, map prepared from maps showing (1) depth to top of Glen Canyon Group and equivalents, (2) thickness of Glen Canyon Group and equivalents (both from Geoffrey Freethey and Gail Cordy, U.S. Geological Survey, written commun., 1984–85); and (3) thickness of Chinle and Moenkopi Formations and equivalents, either from Freethey and Cordy (written commun., 1984–85) in shaded area or Stewart and others (1972a, 1972b) in unshaded area

### Sources for area

**A:** Richmond (1945); Wanless and others (1955)

**B:** Hansen (1965b); Schell (1969)

**C:** Huddle and McCann (1947b); Huddle and others (1951); Bissell (1952); Baker (1976); Bruce Bryant (U.S. Geological Survey, oral commun., 1990)

**D:** Donner (1949); Bass and others (1955); Severy (1955); Sharps (1955); Bass and Northrop (1963); Segerstrom and Young (1972); Stewart and others (1972a, 1972b); Snyder (1980a, 1980b); and American Stratigraphic Company (unpublished drilling logs)

**E:** Hubert (1954); Stewart and others (1972a); Bryant and Martin (1988)

**F:** Welder (1954); Freeman (1971, 1972); Stewart and others (1972a)

**G:** Thomas and others (1945); Mull (1960); Bass and Northrop (1963); Lohman (1965); Gaskill and Godwin (1966a, 1966b); Gaskill and others (1967); Godwin (1968); Stewart and others (1972a, 1972b); Collins (1977); and Maclachlan (1987)

**H:** Eckel and others (1949); Cater (1955a, 1955b); Cater and others (1955); Bush and others (1959, 1960); Donnell (1960); Luedke and Burbank (1962); Stewart and others (1972a); and American Stratigraphic Company (unpublished drilling logs)

**I:** Zapp (1949)

**J:** Harshbarger and Repenning (1954); Strobell (1956); Cooley and others (1964); Stewart and others (1972a); and Hackman and Olson (1977)

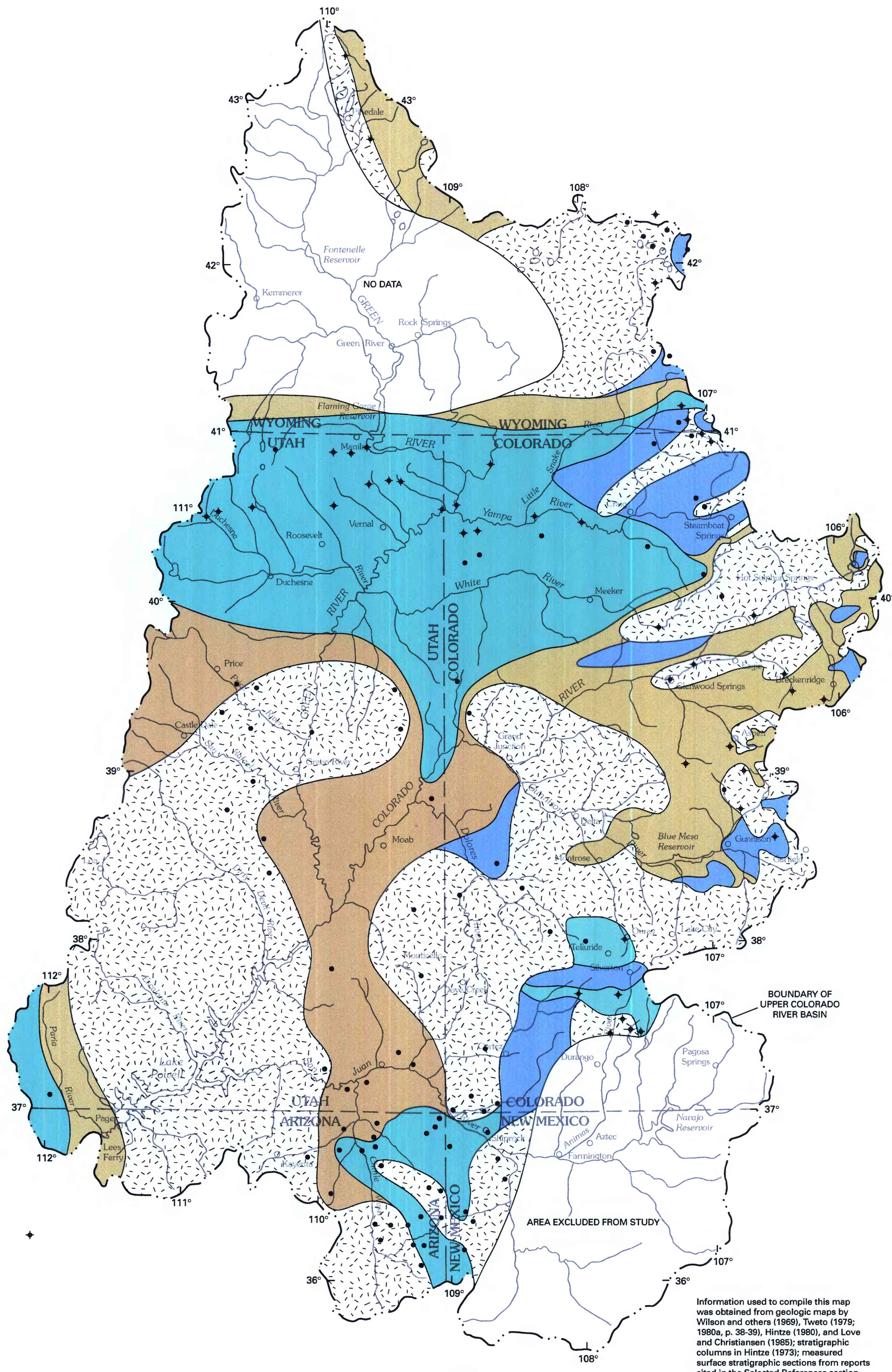
**K:** Gregory and Moore (1931); Phoenix (1963); Witkind and Thaden (1963); Cooley and others (1964); Stewart and others (1972a, 1972b); and American Stratigraphic Company (unpublished drilling logs)

Base from U.S. Geological Survey
U.S. base map, 1:2,500,000

# THICKNESS AND DEPTH TO THE TOP OF THE PALEOZOIC ROCKS THAT COMPRISE HYDROGEOLOGIC UNITS IN THE UPPER COLORADO RIVER BASIN AND VICINITY IN ARIZONA, COLORADO, NEW MEXICO, UTAH, AND WYOMING

By
Arthur L. Geldon
2002

Geldon, A.L., 2002, Geology of Paleozoic rocks in the Upper Colorado River Basin in Arizona, Colorado, New Mexico, Utah, and Wyoming, excluding the San Juan Basin




Information used to compile this map was obtained from geologic maps by Wilson and others (1969), Tweto (1979; 1980a, p. 38-39), Hintze (1980), and Love and Christiansen (1985); stratigraphic columns in Hintze (1973); measured surface stratigraphic sections from reports cited in the Selected References section, and unpublished borehole logs prepared by the American Stratigraphic Company

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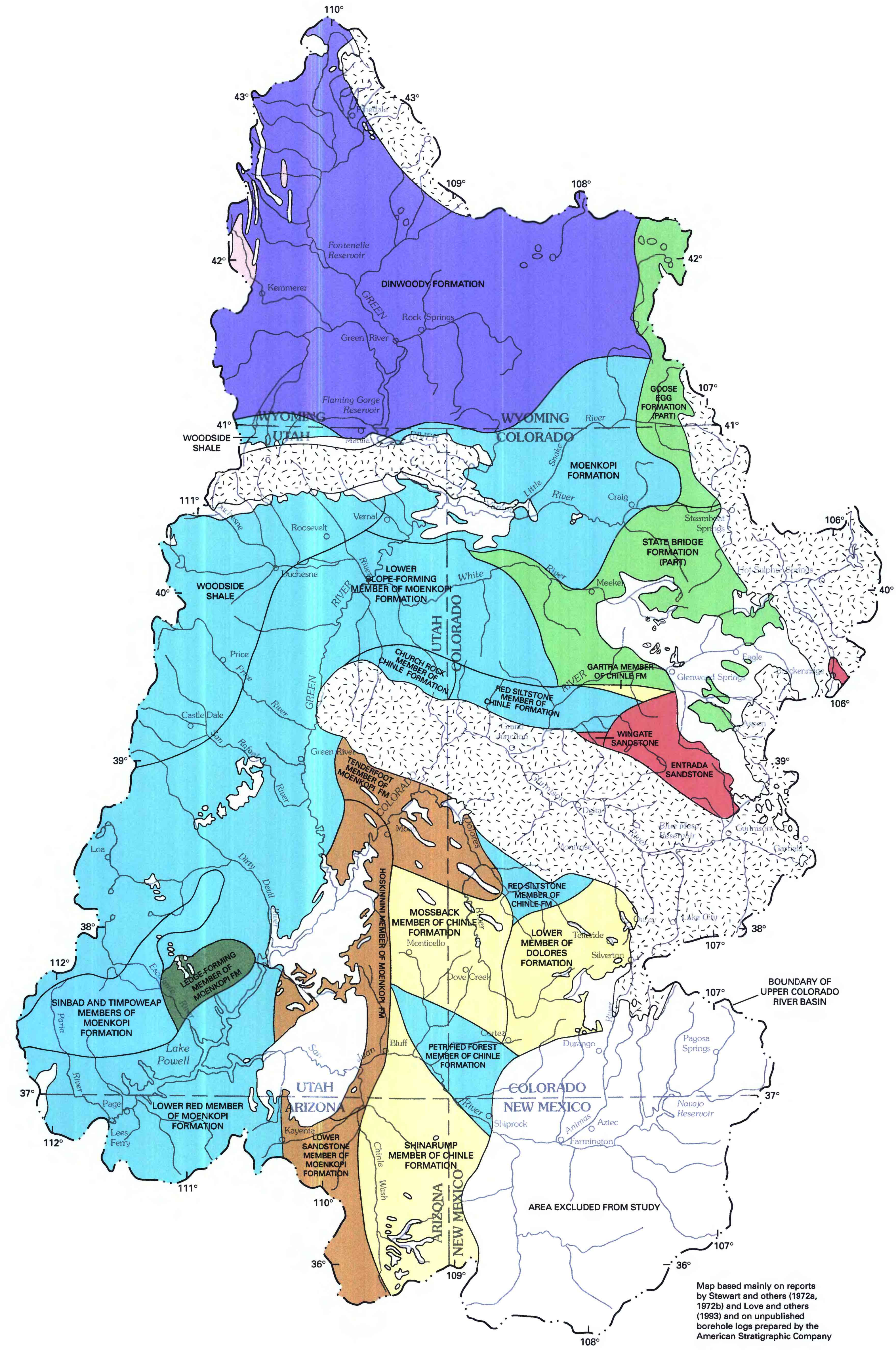
PRECAMBRIAN ROCKS




Map based mainly on reports by Stewart and others (1972a, 1972b) and Love and others (1993) and on unpublished borehole logs prepared by the American Stratigraphic Company

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MESOZOIC ROCKS

## EXPLANATION

### Precambrian rocks

- **Sedimentary rocks and low-grade metamorphic rocks**—Includes the Uinta Mountain, Unkar, and Chuar Groups, Uncompahgre Formation, and unnamed rocks in the Defiance Plateau–Four Corners area
- **Granitic rocks and related intrusives**
- **Metamorphosed sedimentary rocks**—Includes gneiss, schist, quartzite, and marble
- **Metamorphosed volcanic rocks**—Includes greenstone, amphibolite, and meta-tuff
- • **Borehole with lithologic log used to prepare map**
- ✦ **Measured surface stratigraphic section used to prepare map**

### Mesozoic and Paleozoic rocks

**Jurassic**

- **Entrada and Wingate Sandstones**—Tan, white, gray, pink, and red, locally conglomeratic sandstone

**Triassic**

- **Lower Member of Dolores Formation; Gartra, Mossback, and Shinarump Members of Chinle Formation**—Yellow, tan, gray, and orange sandstone and conglomerate with siltstone
- **Hoskinnini and Tenderfoot Members of Moenkopi Formation**—Red and brown sandstone, conglomerate, and siltstone
- **Church Rock, red siltstone, and Petrified Forest Members of Chinle Formation; lower slope-forming and lower red members of Moenkopi Formation; and Woodside Shale**—Generally red, locally gray, green, or variegated claystone and siltstone, with thin sandstone layers
- **Ledge-forming member of Moenkopi Formation**—Red, brown, and gray fine-grained sandstone and siltstone
- **Sinbad and Timpoweap Members of Moenkopi Formation**—Gray, yellow, orange, and green limestone, dolomite, siltstone, and sandstone
- **Dinwoody Formation**—Green and gray shale and limestone with anhydrite
- **Goose Egg and State Bridge Formations (upper part)**—Mostly red and brown, locally green siltstone and claystone with thin sandstone, anhydrite, and carbonate layers
- **Mesozoic rocks eroded or not deposited**—Paleozoic rocks overlain by Tertiary Wasatch Formation
- **Mesozoic and Paleozoic rocks thrust beneath Precambrian rocks or area in which Mesozoic and Paleozoic rocks are missing because of erosion or nondeposition**
- **Area where Paleozoic rocks crop out**

Base from U.S. Geological Survey
U.S. base map, 1:2,500,000

# PRECAMBRIAN AND MESOZOIC ROCKS IN CONTACT WITH PALEOZOIC ROCKS OF THE UPPER COLORADO RIVER BASIN IN ARIZONA, COLORADO, NEW MEXICO, UTAH, AND WYOMING, EXCLUDING PARTS OF THE SAN JUAN BASIN

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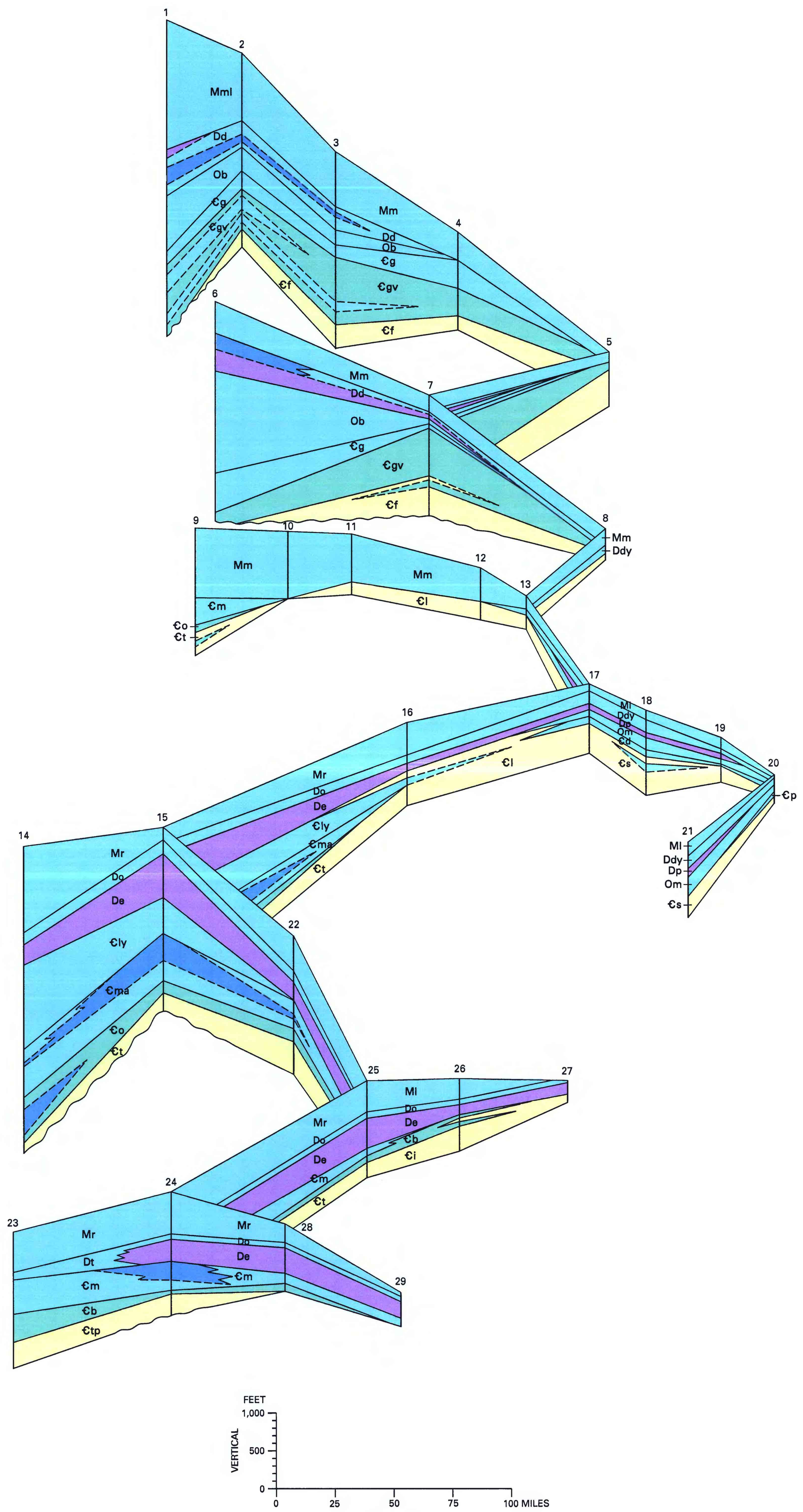
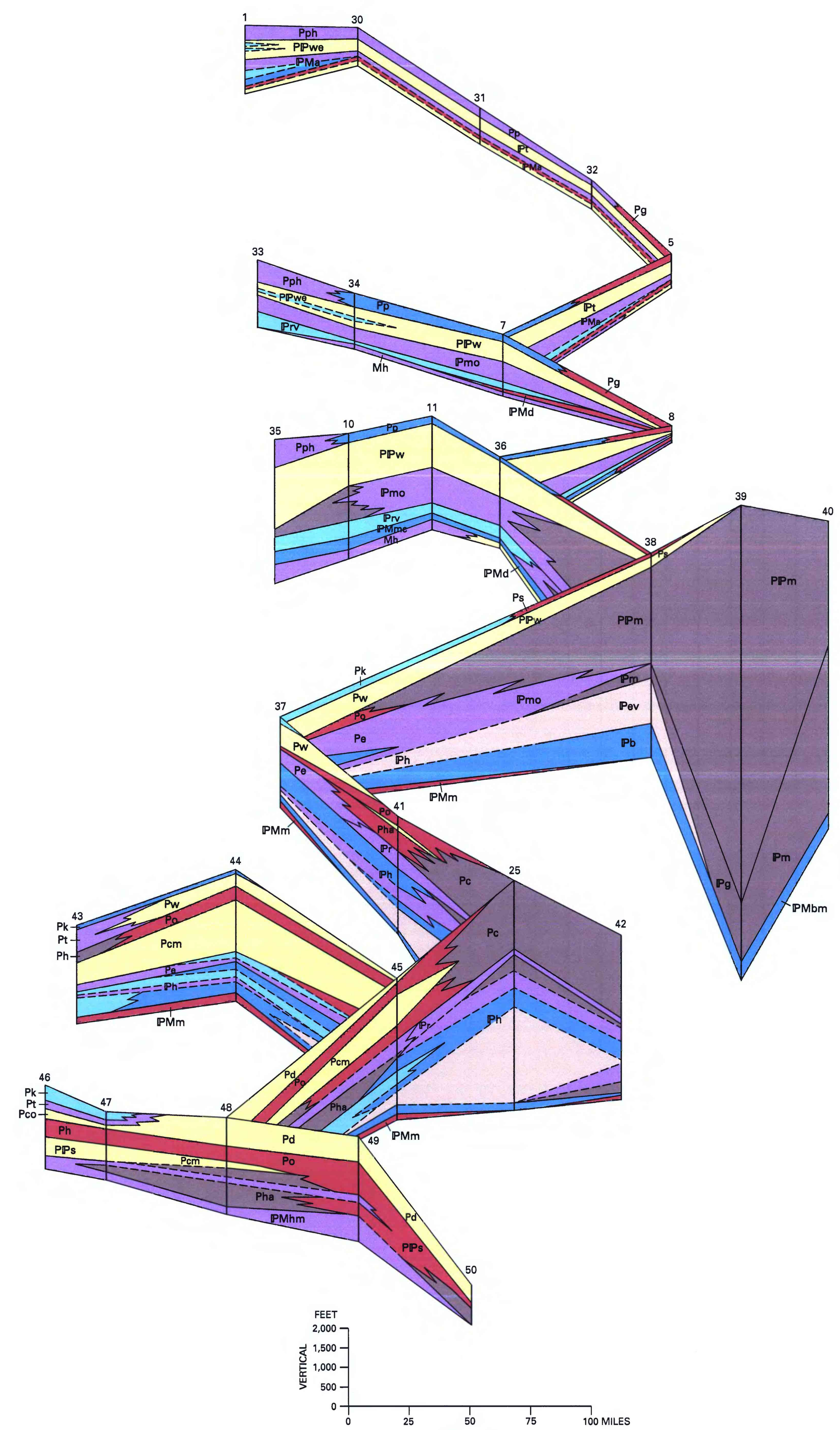


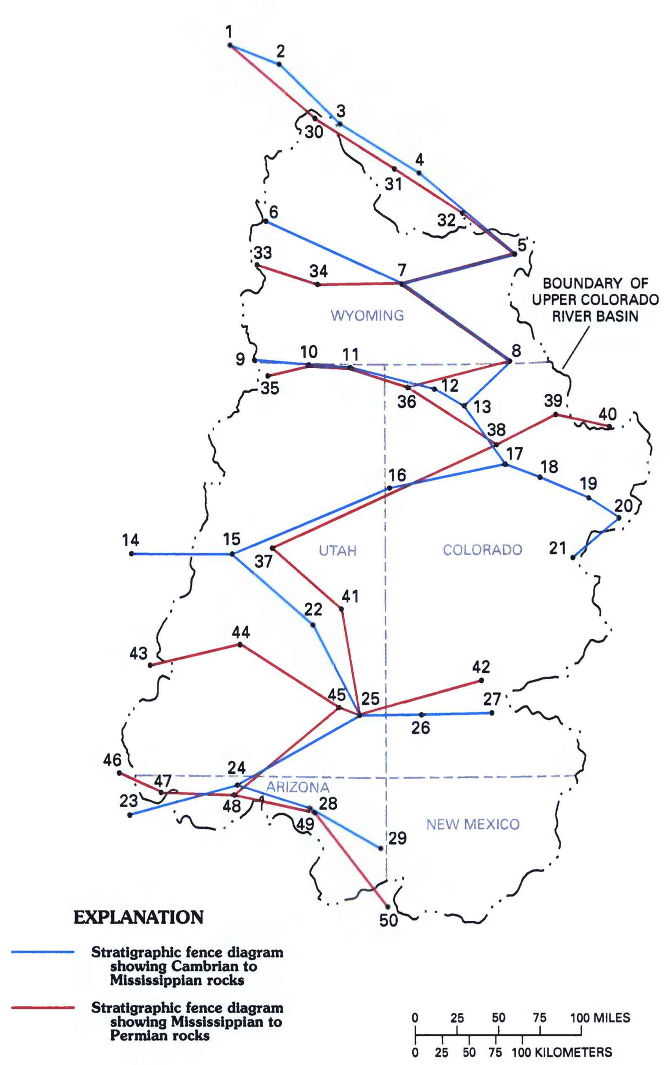

CAMBRIAN TO MISSISSIPPIAN ROCKS




MISSISSIPPIAN TO PERMIAN ROCKS

### Localities

1 Snake River Canyon (Wanless and others, 1959)
2 Granite Creek (Foster, 1947; Wanless and others, 1959)
3 Boulder area (Love, 1950)
4 Beaver Creek (Keefer and Van Lieu, 1966)
5 Rawlins area (Berry, 1960)
6 Amerada 1-Fossil (American Stratigraphic Co., unpublished)
7 Champlin 1-Brady 12–11 (American Stratigraphic Co., unpublished)
8 Gulf 1-Slater Creek (American Stratigraphic Co., unpublished)
9 Lake Fork (Huddle and others, 1951)
10 Whiterocks River (Kinney, 1955)
11 Diamond Mountain (Ritzma, 1959)
Johnson Draw (Untermann and Untermann, 1954)
12 Cross Mountain (Wilson, 1957)
13 Juniper Mountain (Abrassart and Clough, 1955)
14 Tenneco 1-Antimony Canyon (American Stratigraphic Co., unpublished)
15 American Metals Climax 1-Red Hills (American Stratigraphic Co., unpublished)
16 General Petroleum 1-Schutte (American Stratigraphic Co., unpublished)
17 Northwestern White River Plateau (Hallgarth, 1959)
18 Southeastern White River Plateau (Bass and Northrop, 1963)
19 Minturn area (Tweto and Lovering, 1977)
20 Hoosier Pass area (Singewald, 1951)
21 Cement Creek (Mallory, 1957)
22 Midwest Exploration 1-Elk Ridge (American Stratigraphic Co., unpublished)
23 Bass Trail (Noble, 1922)
24 Sinclair 1-Navajo (American Stratigraphic Co., unpublished)
25 Shell 1-Bluff (American Stratigraphic Co., unpublished)
26 Gulf 1-Fulks (American Stratigraphic Co., unpublished)
27 Stag Mesa (Baars and Knight, 1957)
28 Cactus Drilling 1-Navajo 85–15 (American Stratigraphic Co., unpublished)
29 Union 1-Navajo 166 (American Stratigraphic Co., unpublished)
30 Sheep Mountain (Richmond, 1945)
31 Squaw Creek (Keefer and Van Lieu, 1966)
32 California 3-Green Mountain (American Stratigraphic Co., unpublished)
33 Exxon 1-Bullpen Creek (American Stratigraphic Co., unpublished)
34 Mountain Fuel Supply 1-Broff (American Stratigraphic Co., unpublished)
35 Rock Creek (Huddle and others, 1951)
36 Hells Canyon (Thomas and others, 1945)
37 Black Box, composite (Gilluly, 1929; American Stratigraphic Co., unpublished)
38 Main Elk Creek (Thomas and others, 1945; Bass and Northrop, 1963)
39 Elk Mountains, composite (Mallory, 1957; Bryant, 1979)
40 Pando area (Tweto, 1949)
41 Pan American 1-Charles (American Stratigraphic Co., unpublished)
42 Animas River (Larsen and Cross, 1956; Wengerd, 1957)
43 Tenneco 1-Johns Valley (American Stratigraphic Co., unpublished)
44 Superior 14–2 (American Stratigraphic Co., unpublished)
45 Comb Wash, composite (Gregory, 1938; American Stratigraphic Co., unpublished)
46 Underwood 1–32 Jacob Lake (American Stratigraphic Co., unpublished)
47 Lees Ferry area, composite (Phoenix, 1963; McKee, 1982)
48 Sinclair 1-Navajo (American Stratigraphic Co., unpublished)
49 Tenneco 1-Navajo 8939 (American Stratigraphic Co., unpublished)
50 Bonito Canyon (Read and Wanek, 1961)




INDEX MAP TO FENCE DIAGRAMS

## EXPLANATION

### Rock Types

- Quartz sandstone and quartzite
- Arkosic and graywacke sandstone
- Red shale and fine-grained sandstone
- Glauconitic and micaceous shale and fine-grained sandstone
- Gray shale, limestone, and dolomite
- Limestone and dolomite
- Limestone, dolomite, sandstone, and shale
- Anhydrite and halite with shale and carbonate interbeds

### Line Symbols

- Contact between geologic formations or groups
- Contact between different lithologies within a geologic formation or group
- Base of Paleozoic rocks uncertain because of incomplete penetration by boreholes or measurement of surface stratigraphic sections in vicinity
- Borehole or measured surface stratigraphic section. Boreholes are indicated by reference to American Statigraphic Company

### Symbols Used for Geologic Units

#### Permian

| | | | |
|---|---|---|---|
| Pc | Cutler Formation | Pk | Kaibab Formation |
| Pcm | Cedar Mesa Sandstone of Baars (1962) | Po | Organ Rock Shale of Baars (1962) |
| Pco | Coconino Sandstone | Pp | Park City Formation of McKelvey and others (1959) |
| Pd | De Chelly Sandstone | Pph | Phosphoria Formation of McKelvey and others (1959) |
| Pe | Elephant Canyon Formation of Baars (1962) | Psc | Schoolhouse Member of Maroon Formation |
| Pg | Goose Egg Formation, lower part | Ps | State Bridge Formation, lower part |
| Ph | Hermit Shale | Pt | Toroweap Formation |
| Pha | Halgaito Shale of Baars (1962) | Pw | White Rim Sandstone of Baars (1962) |

#### Permian and Pennsylvanian

| | | | |
|---|---|---|---|
| PIPm | Maroon Formation | PIPw | Weber Sandstone |
| PIPs | Supai Formation or Group | PIPwe | Wells Formation |

#### Pennsylvanian

| | | | |
|---|---|---|---|
| IPb | Belden Formation | IPm | Minturn Formation |
| IPev | Eagle Valley Evaporite | IPmo | Morgan Formation |
| IPg | Gothic Formation of Langenheim (1952) | IPr | Rico Formation |
| IPh | Hermosa Formation | IPrv | Round Valley Limestone |
| | | IPt | Tensleep Sandstone |

#### Pennsylvanian and Mississippian

| | | | |
|---|---|---|---|
| IPMa | Amsden Formation | IPMhm | Hermosa and Molas Formations |
| IPMbm | Belden and Molas Formations | IPMm | Molas Formation |
| IPMd | Doughnut Shale | IPMmc | Manning Canyon Shale |

#### Mississippian

| | | | |
|---|---|---|---|
| Mh | Humbug Formation | Mm | Madison Limestone |
| Ml | Leadville Limestone | Mml | Mission Canyon and Lodgepole Limestones |
| | | Mr | Redwall Limestone |

#### Devonian

| | | | |
|---|---|---|---|
| Dd | Darby Formation | Do | Ouray Limestone |
| Ddy | Dyer Dolomite | Dp | Parting Formation |
| De | Elbert Formation | Dt | Temple Butte Formation |

#### Ordovician

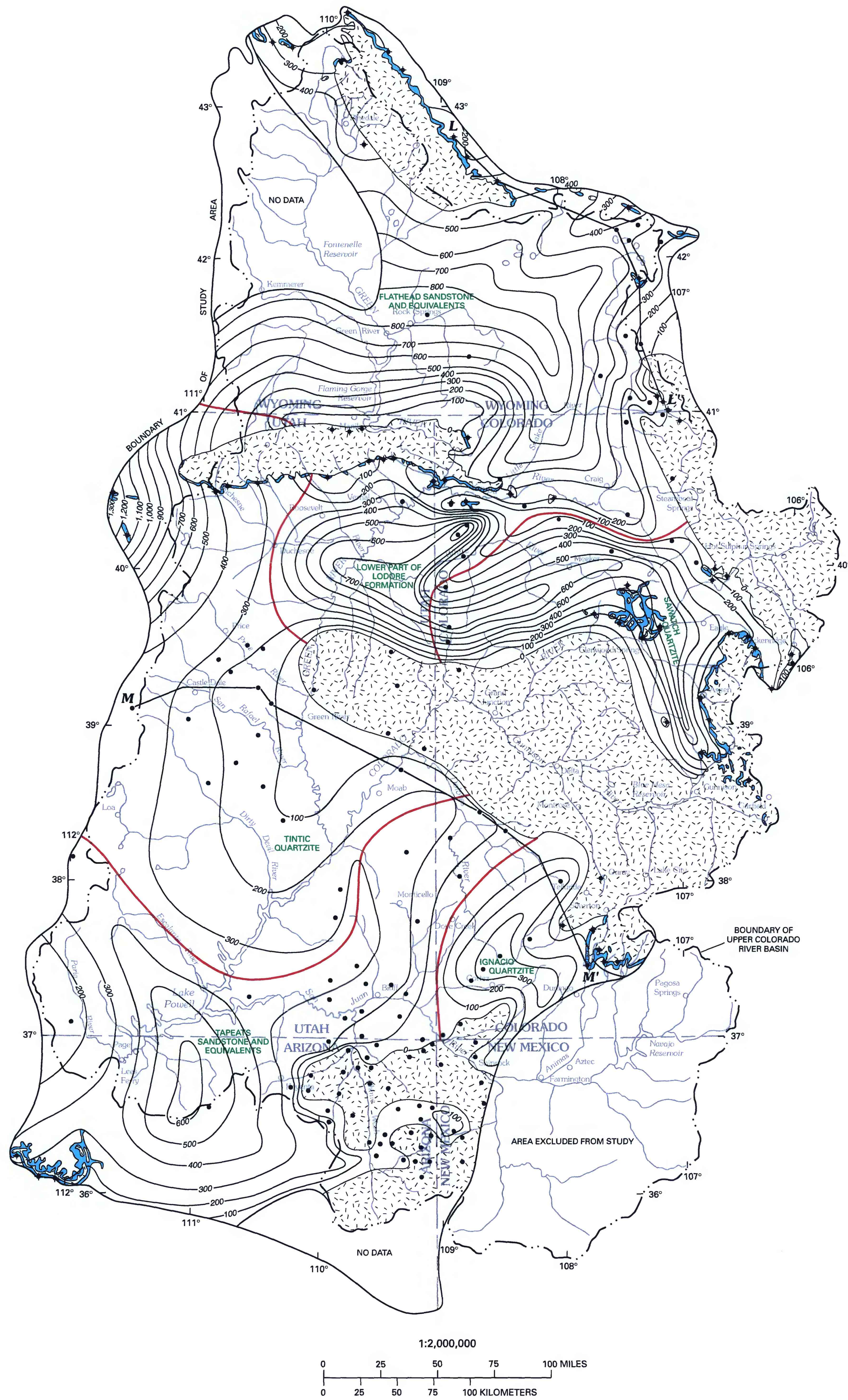
| | | | |
|---|---|---|---|
| Ob | Bighorn Dolomite | Om | Manitou Dolomite |

#### Cambrian

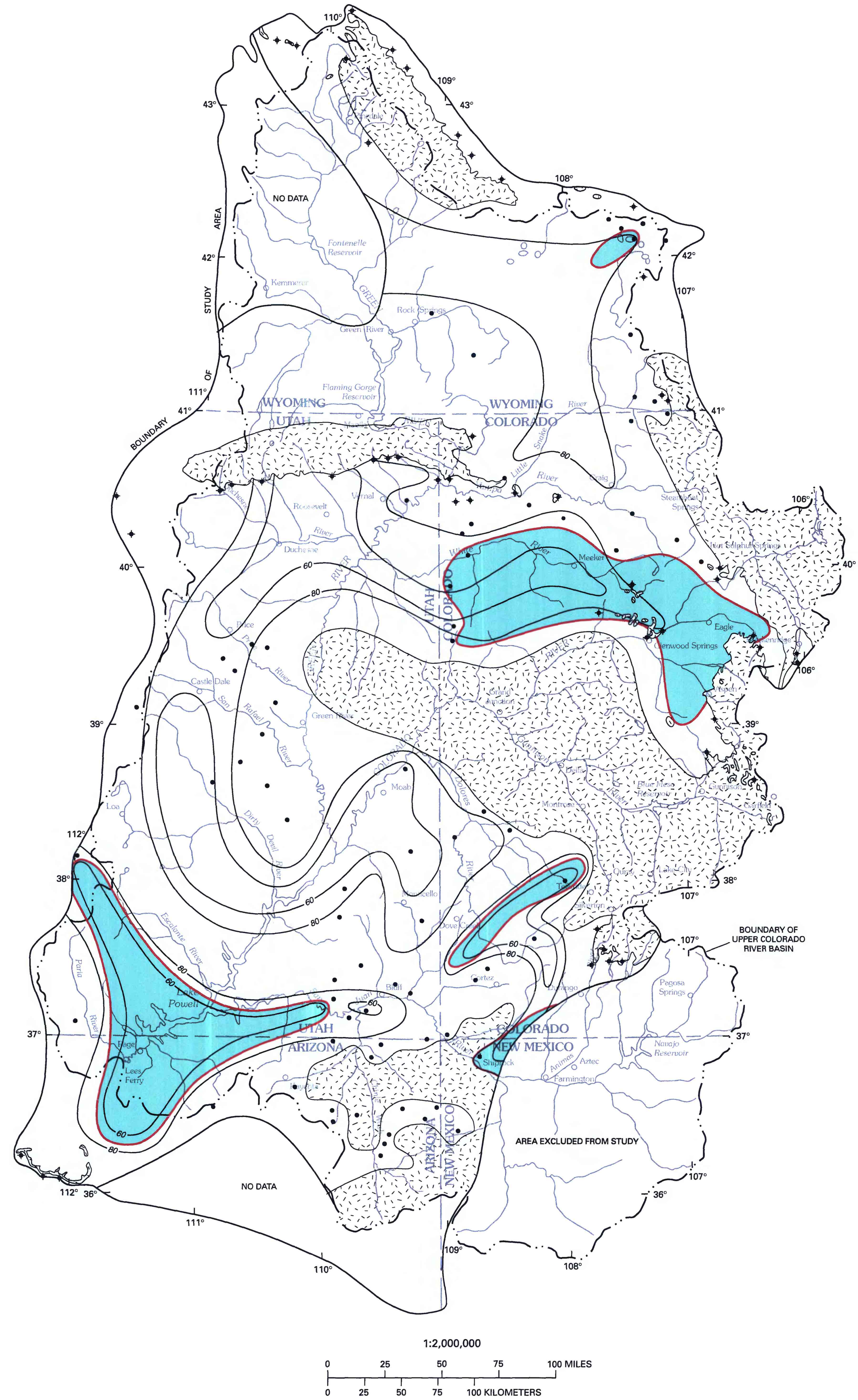
| | | | |
|---|---|---|---|
| Єb | Bright Angel Shale and equivalents | Єly | Lynch Dolomite |
| Єd | Dotsero Formation | Єm | Muav Limestone and equivalents |
| Єf | Flathead Sandstone | Єma | Maxfield Limestone |
| Єg | Gallatin Limestone | Єo | Ophir Shale |
| Єgv | Gros Ventre Formation | Єp | Peerless Formation |
| Єi | Ignacio Quartzite | Єs | Sawatch Quartzite |
| Єl | Lodore Formation | Єt | Tintic Quartzite |
| | | Єtp | Tapeats Sandstone and equivalents |

# CHANGES IN STRATIGRAPHIC NOMENCLATURE AND LITHOLOGY WITHIN THE PALEOZOIC ROCKS OF THE UPPER COLORADO RIVER BASIN IN ARIZONA, COLORADO, NEW MEXICO, UTAH, AND WYOMING, EXCLUDING PARTS OF THE SAN JUAN BASIN

By
Arthur L. Geldon
2002




STRATIGRAPHIC NOMENCLATURE AND THICKNESS




LITHOLOGY

## EXPLANATION

Area where Flathead aquifer is missing because of erosion or nondeposition or thrust under Precambrian rocks

• Borehole with lithologic log used to prepare map

✦ Measured surface stratigraphic section used to prepare map

### Stratigraphic Nomenclature and Thickness

Area where Flathead aquifer crops out (generalized)

—100— **Line of equal thickness**—Approximately located in southwestern Wyoming and northeastern Utah because of sparse control. Interval is 100 feet

Approximate boundary between component geologic units

*L* —— *L'* Location of stratigraphic cross section shown in figures 12 and 13

### Lithology

Quartzitic, dolomitic, and glauconitic sandstone and quartzite with conglomerate and shale interbeds

Quartzitic, dolomitic, and glauconitic sandstone and quartzite with conglomerate and shale interbeds and 5 to 20 percent interbedded limestone and dolomite

—60— **Line of equal percent sandstone, quartzite, and conglomerate**—Location is approximate because of generally sparse control. Interval is 20 percent

Approximate boundary between lithofacies

Base from U.S. Geological Survey
U.S. base map, 1:2,500,000

# STRATIGRAPHIC NOMENCLATURE, THICKNESS, AND LITHOLOGY OF THE FLATHEAD AQUIFER IN THE UPPER COLORADO RIVER BASIN AND VICINITY IN ARIZONA, COLORADO, NEW MEXICO, UTAH, AND WYOMING

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Arthur L. Geldon
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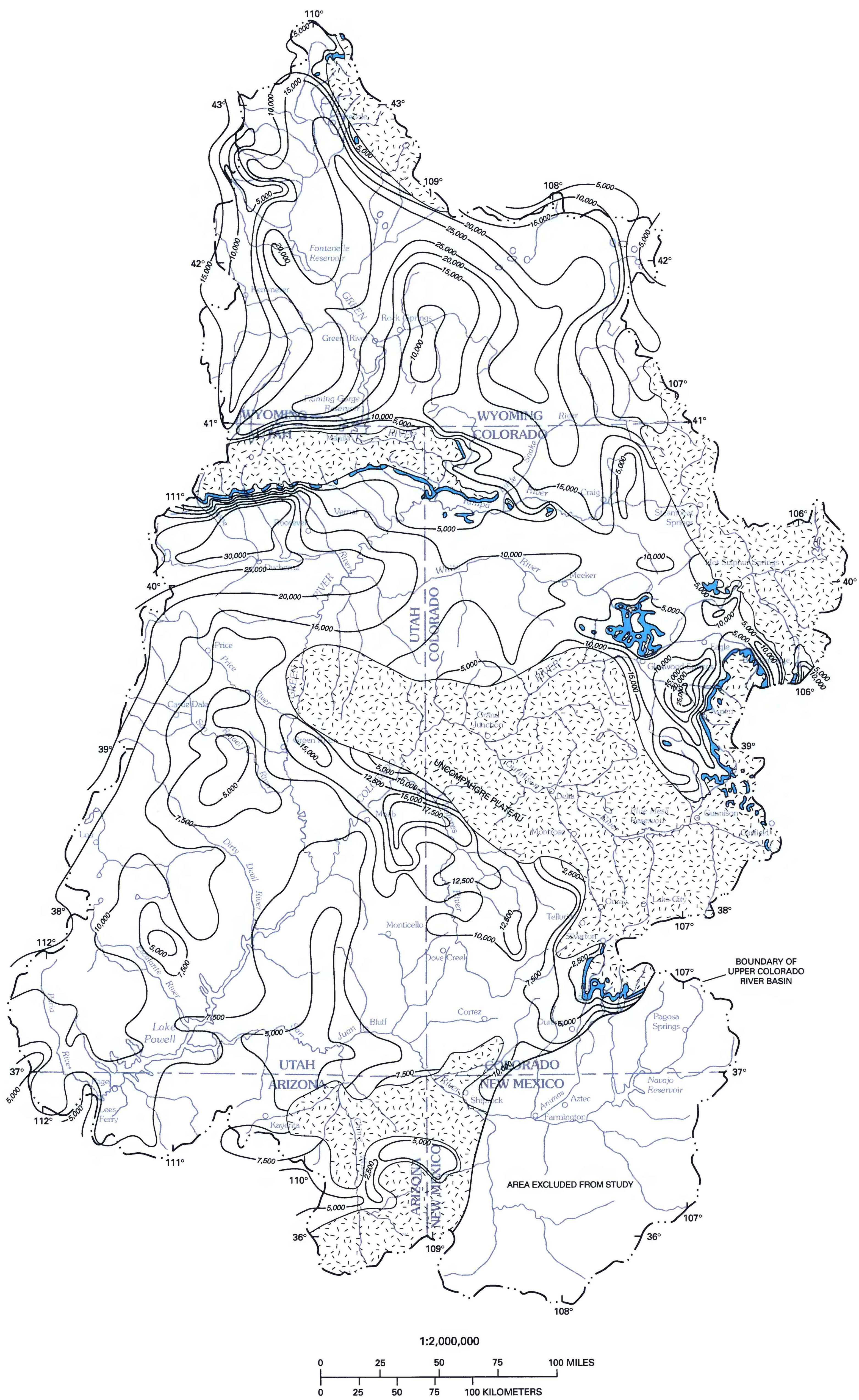
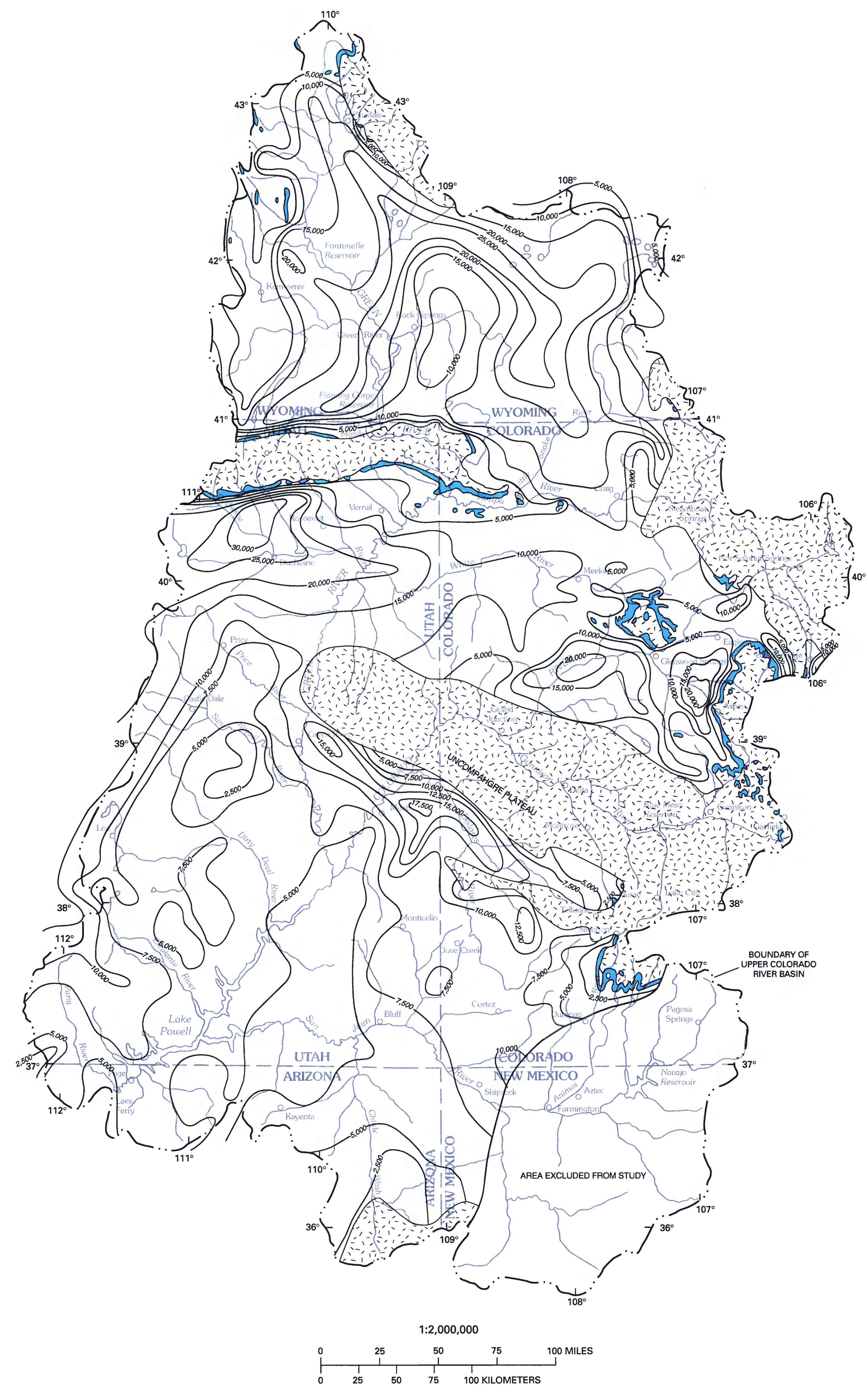
PROFESSIONAL PAPER 1411–A
Depths to top of Flathead and Madison aquifers—PLATE 7
Geldon, A.L., 2002, Geology of Paleozoic rocks in the Upper Colorado River Basin in Arizona, Colorado, New Mexico, Utah, and Wyoming, excluding the San Juan Basin




DEPTH TO TOP OF FLATHEAD AQUIFER




DEPTH TO TOP OF MADISON AQUIFER

**EXPLANATION**

- Area where aquifer to which depth is shown crops out (generalized)
- Area where aquifer to which depth is shown is missing because of erosion or nondeposition or is thrust under Precambrian rocks
- —5,000— Line of equal depth of top of aquifer—Interval is 5,000 feet, except south and west of Uncompahgre Plateau, where interval is 2,500 feet

Base from U.S. Geological Survey
U.S. base map, 1:2,500,000

# DEPTHS TO THE TOP OF THE FLATHEAD AND MADISON AQUIFERS IN THE UPPER COLORADO RIVER BASIN AND VICINITY IN ARIZONA, COLORADO, NEW MEXICO, UTAH, AND WYOMING

By
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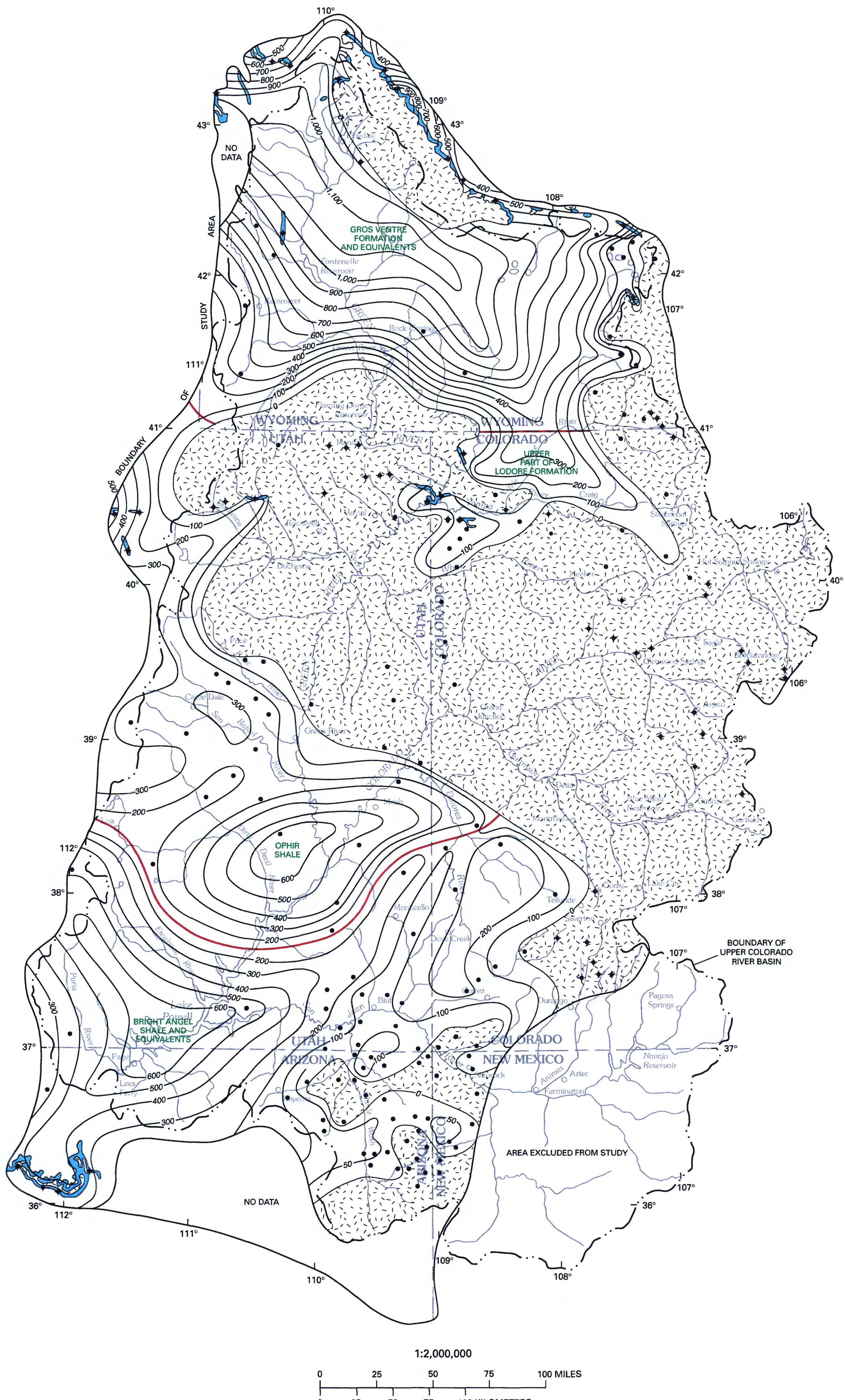
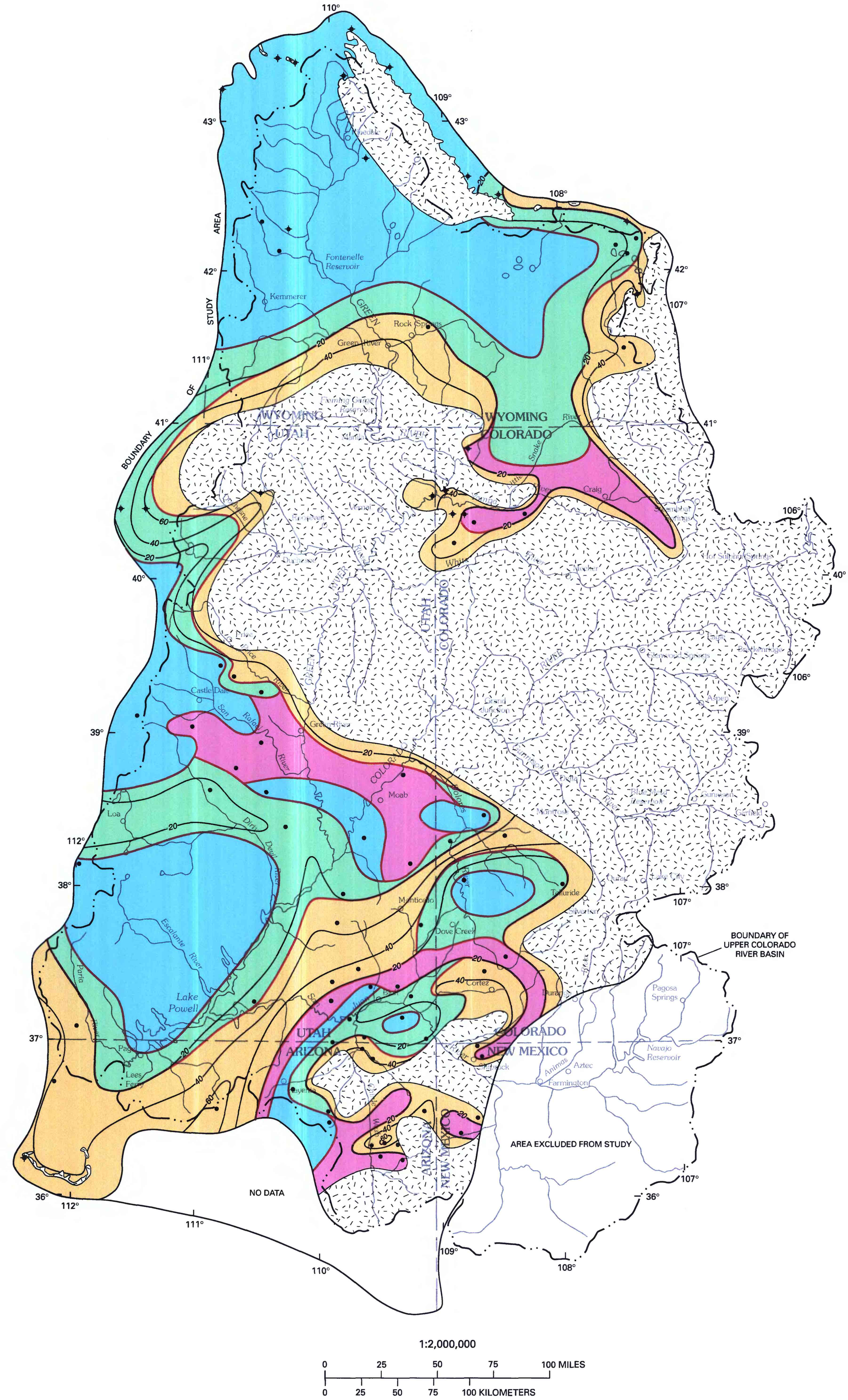



STRATIGRAPHIC NOMENCLATURE AND THICKNESS




LITHOLOGY

## EXPLANATION

Area where Gros Ventre confining unit is missing because of erosion or nondeposition or thrust under Precambrian rocks

• Borehole with lithologic log used to prepare map

✦ Measured surface stratigraphic section used to prepare map

**Stratigraphic Nomenclature and Thickness**

Area where Gros Ventre confining unit crops out (generalized)

—200— **Line of equal thickness**—Interval is 100 feet, except in northeastern corner of Arizona, where interval is 50 feet

Approximate boundary between component geologic units

**Lithology**

Siltstone and claystone, with less than 10 percent, each, sandstone and carbonate rocks

Siltstone and claystone, with 10–70 percent sandstone and less than 10 percent carbonate rocks

Siltstone and claystone, with 10–50 percent carbonate rocks and less than 10 percent sandstone

Siltstone and claystone, with sandstone and carbonate rocks each greater than 10 percent and together generally no more than 50 percent of the unit

—20— **Line of equal percent sandstone**—Location is approximate because of sparse control. Interval is 20 percent

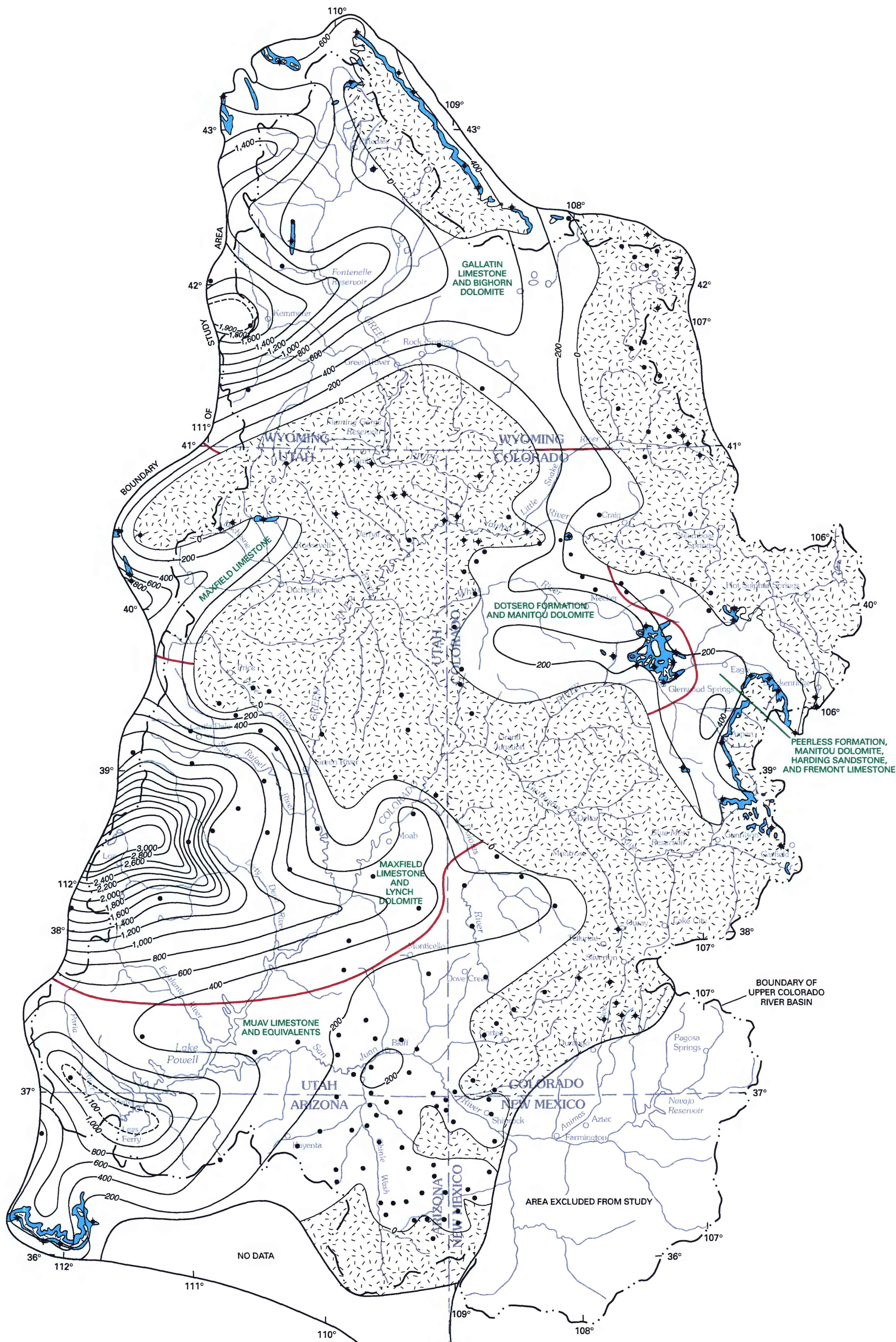
Approximate boundary between lithofacies

Base from U.S. Geological Survey
U.S. base map, 1:2,500,000

# STRATIGRAPHIC NOMENCLATURE, THICKNESS, AND LITHOLOGY OF THE GROS VENTRE CONFINING UNIT IN THE UPPER COLORADO RIVER BASIN AND VICINITY IN ARIZONA, COLORADO, NEW MEXICO, UTAH, AND WYOMING

By
Arthur L. Geldon
2002

Geldon, A.L., 2002, Geology of Paleozoic rocks in the Upper Colorado River Basin in Arizona, Colorado, New Mexico, Utah, and Wyoming, excluding the San Juan Basin

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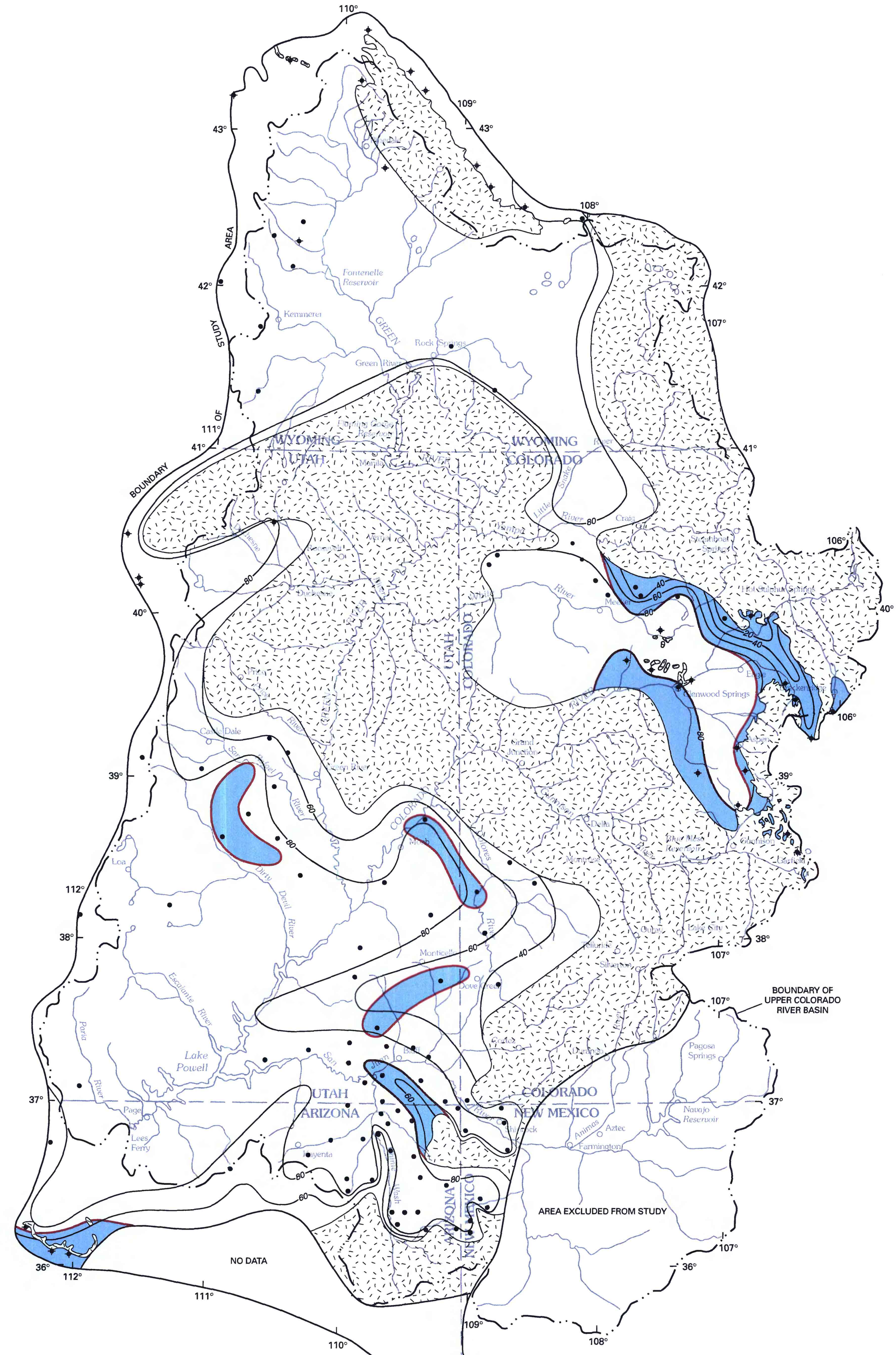
0 25 50 75 100 MILES

0 25 50 75 100 KILOMETERS

STRATIGRAPHIC NOMENCLATURE AND THICKNESS




1:2,000,000

0 25 50 75 100 MILES

0 25 50 75 100 KILOMETERS

LITHOLOGY

## EXPLANATION

- Area where Bighorn aquifer is missing because of erosion or nondeposition or thrust under Precambrian rocks
- • Borehole with lithologic log used to prepare map
- ✦ Measured surface stratigraphic section used to prepare map

**Stratigraphic Nomenclature and Thickness**

- Area where Bighorn aquifer crops out (generalized)
- —400— **Line of equal thickness**—Interval is 200 feet. In the southwestern corner of the area, the 1,100-foot contour is shown to aid interpretation. In Wyoming, the 1,900-foot contour is shown
- Approximate boundary between component geologic units

**Lithology**

- Limestone and dolomite with shale interbeds and generally less than 5 percent sandstone interbeds
- Limestone and dolomite with shale and sandstone interbeds that locally exceed the carbonate rocks in abundance
- —60— **Line of equal percent carbonate rocks**—Location generally is approximate. Interval is 20 percent
- Approximate boundary between lithofacies

Base from U.S. Geological Survey
U.S. base map, 1:2,500,000

# STRATIGRAPHIC NOMENCLATURE, THICKNESS, AND LITHOLOGY OF THE BIGHORN AQUIFER IN THE UPPER COLORADO RIVER BASIN AND VICINITY IN ARIZONA, COLORADO, NEW MEXICO, UTAH, AND WYOMING

By
Arthur L. Geldon
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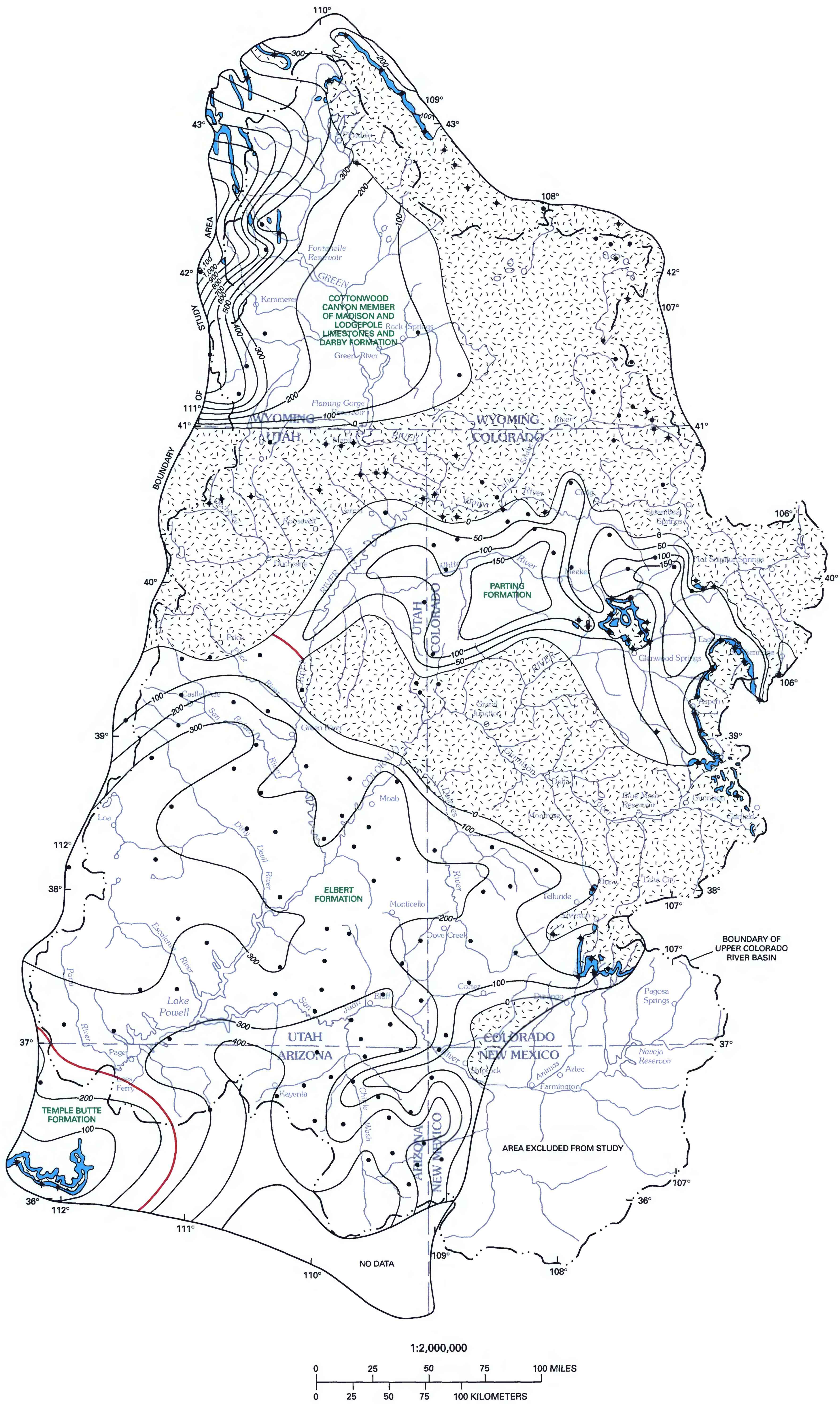
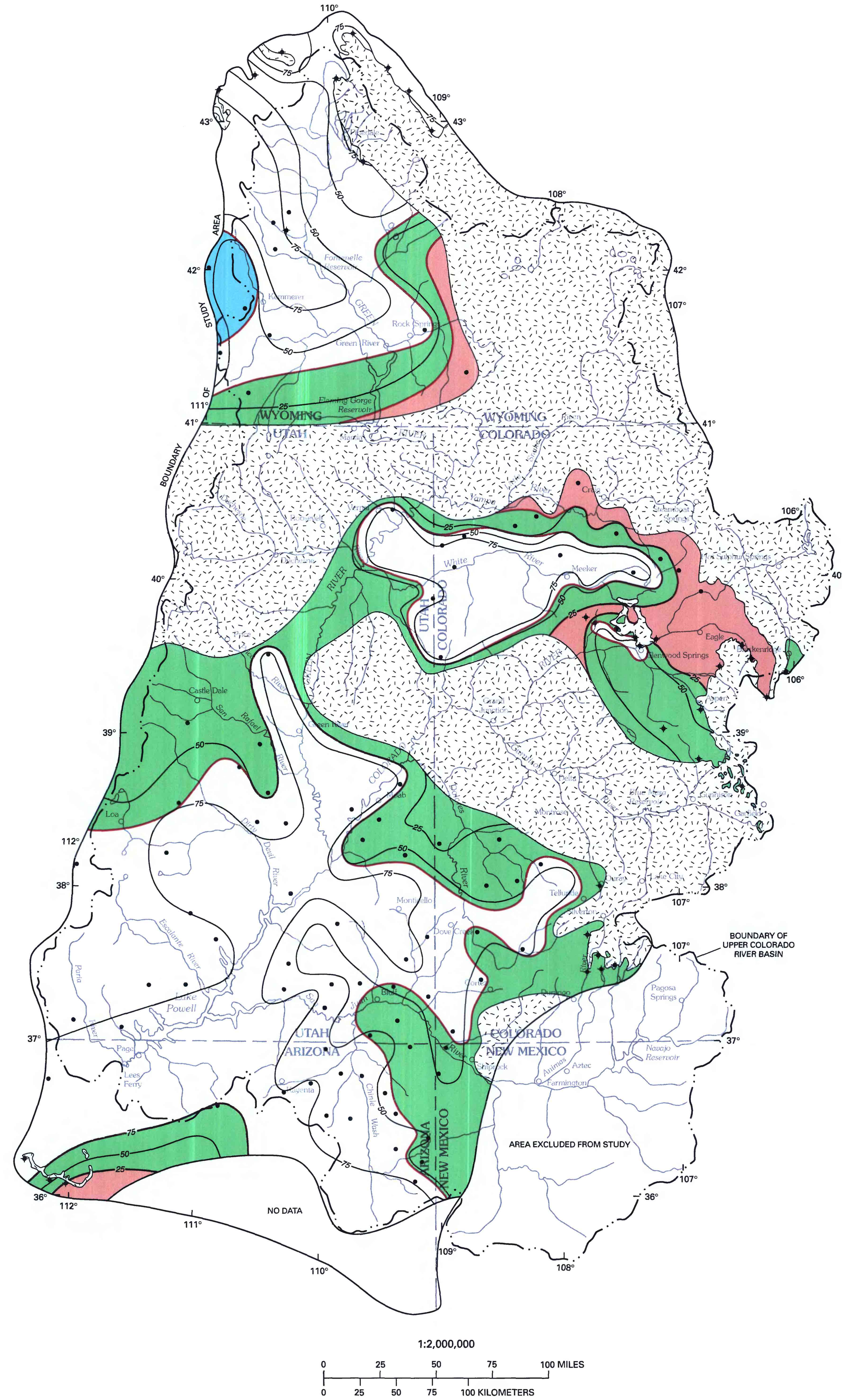
Geldon, A.L., 2002, Geology of Paleozoic rocks in the Upper Colorado River Basin in Arizona, Colorado, New Mexico, Utah, and Wyoming, excluding the San Juan Basin




STRATIGRAPHIC NOMENCLATURE AND THICKNESS




LITHOLOGY

## EXPLANATION

Area where Elbert-Parting confining unit is missing because of erosion or nondeposition or thrust under Precambrian rocks

• Borehole with lithologic log used to prepare map

✦ Measured surface stratigraphic section used to prepare map

### Stratigraphic Nomenclature and Thickness

Area where Elbert-Parting confining unit crops out (generalized)

—*100*— **Line of equal thickness**—Interval is 100 feet, except in Parting Formation depositional area, where interval is 50 feet

Approximate boundary between component geologic units

### Lithology

Dolomite, limestone, and shale, with less than 20 percent sandstone and quartzite interbeds

Dolomite, limestone, and shale, with 5–10 percent anhydrite and less than 25 percent sandstone and quartzite interbeds

Dolomite, limestone, sandstone, quartzite, and shale

Sandstone, quartzite, and shale, with less than 25 percent limestone and dolomite interbeds

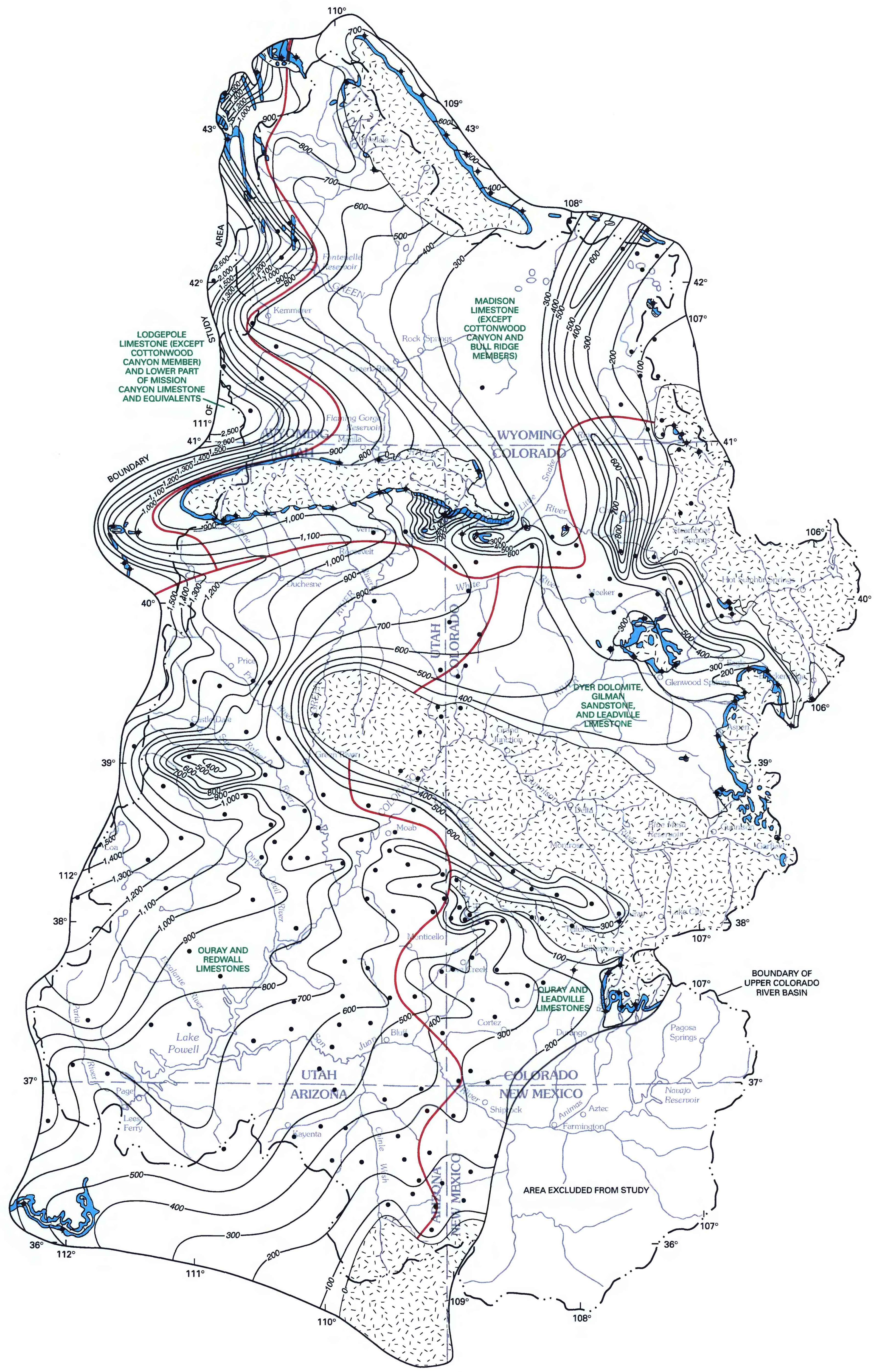
—*25*— **Line of equal percent carbonate rocks**—Location generally is approximate because of sparse control. Interval is 25 percent

Approximate boundary between lithofacies

Base from U.S. Geological Survey
U.S. base map, 1:2,500,000

# STRATIGRAPHIC NOMENCLATURE, THICKNESS, AND LITHOLOGY OF THE ELBERT-PARTING CONFINING UNIT IN THE UPPER COLORADO RIVER BASIN AND VICINITY IN ARIZONA, COLORADO, NEW MEXICO, UTAH, AND WYOMING

By
Arthur L. Geldon
2002

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0 25 50 75 100 MILES

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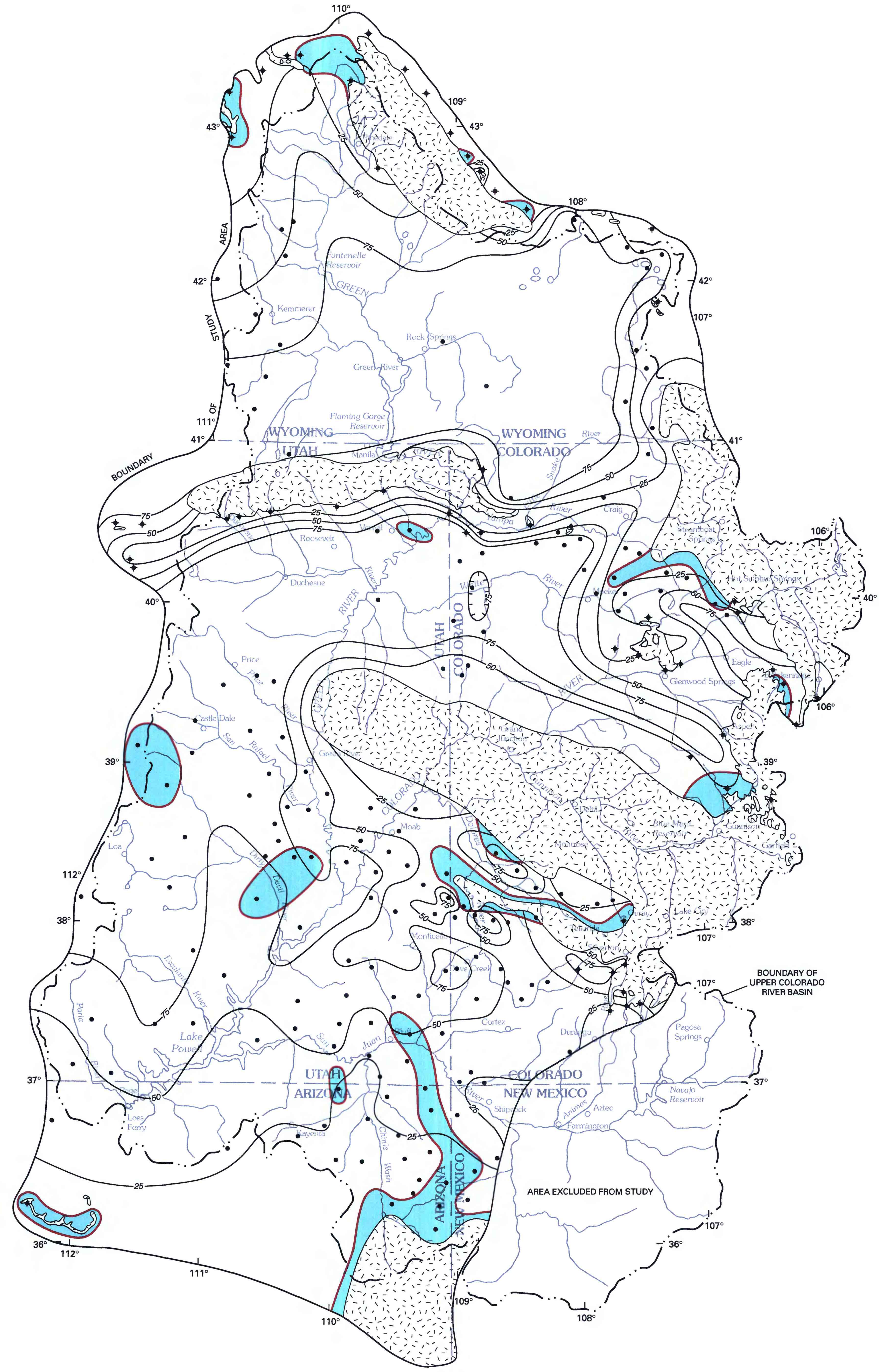
STRATIGRAPHIC NOMENCLATURE AND THICKNESS




1:2,000,000

0 25 50 75 100 MILES

0 25 50 75 100 KILOMETERS

LITHOLOGY

## EXPLANATION

- Area where Redwall-Leadville zone is missing because of erosion or nondeposition or thrust under Precambrian rocks
- • Borehole with lithologic log used to prepare map
- + Measured surface stratigraphic section used to prepare map

### Stratigraphic Nomenclature and Thickness

- Area where Redwall-Leadville zone crops out (generalized)
- —300— Line of equal thickness—Interval is 100 feet, except in the Overthrust Belt area of Wyoming, where interval is 500 feet
- Approximate boundary between component geologic units

### Lithology

- Limestone and dolomite, locally brecciated or marbleized, with less than 5 percent sandstone and shale interbeds
- Limestone and dolomite, locally brecciated or marbleized, with 5–10 percent sandstone and shale interbeds
- —25— Line of equal percent dolomite—Interval is 25 percent
- Approximate boundary between lithofacies

Base from U.S. Geological Survey
U.S. base map, 1:2,500,000

# STRATIGRAPHIC NOMENCLATURE, THICKNESS, AND LITHOLOGY OF THE REDWALL-LEADVILLE ZONE OF THE MADISON AQUIFER IN THE UPPER COLORADO RIVER BASIN AND VICINITY IN ARIZONA, COLORADO, NEW MEXICO, UTAH, AND WYOMING

By
Arthur L. Geldon
2002

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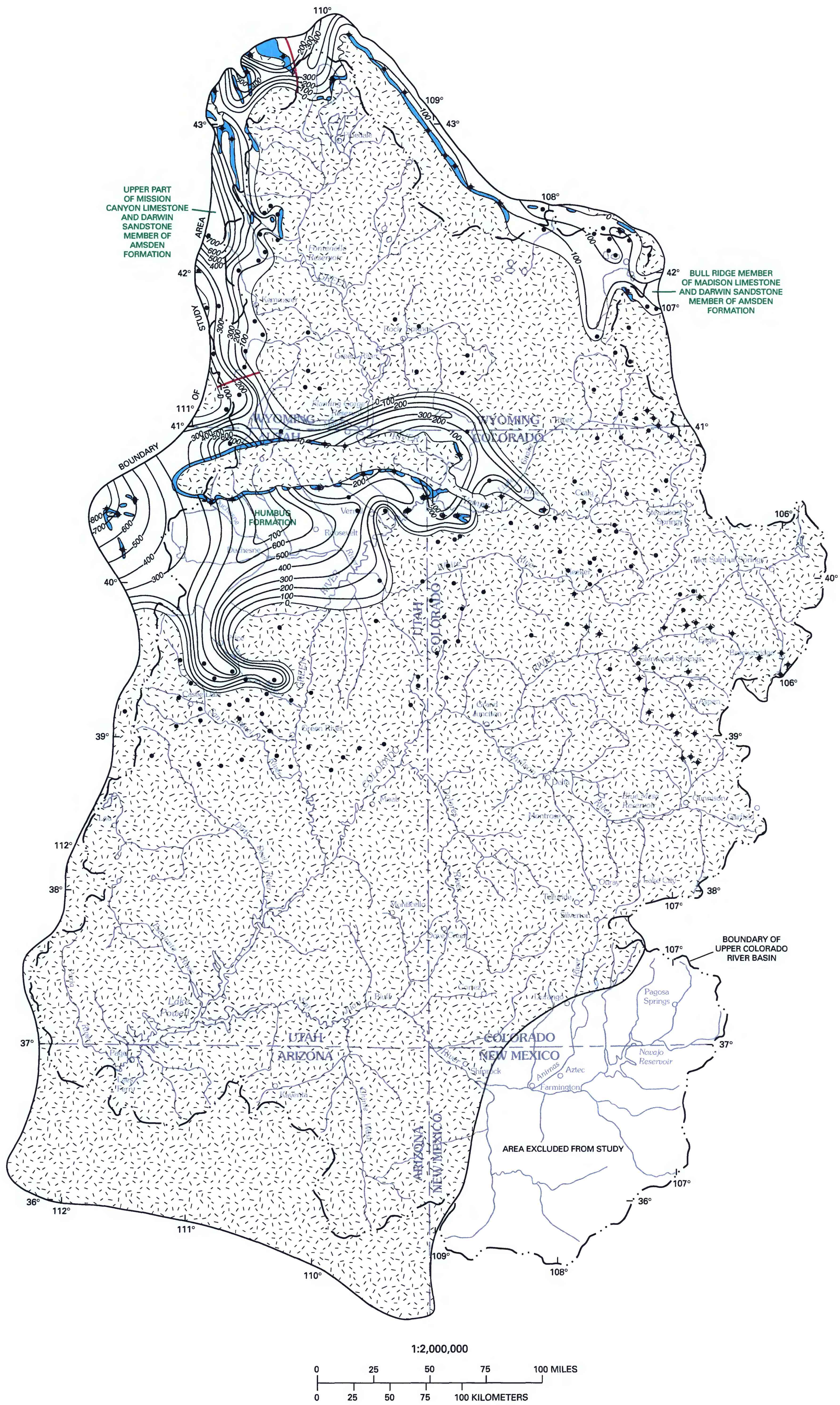
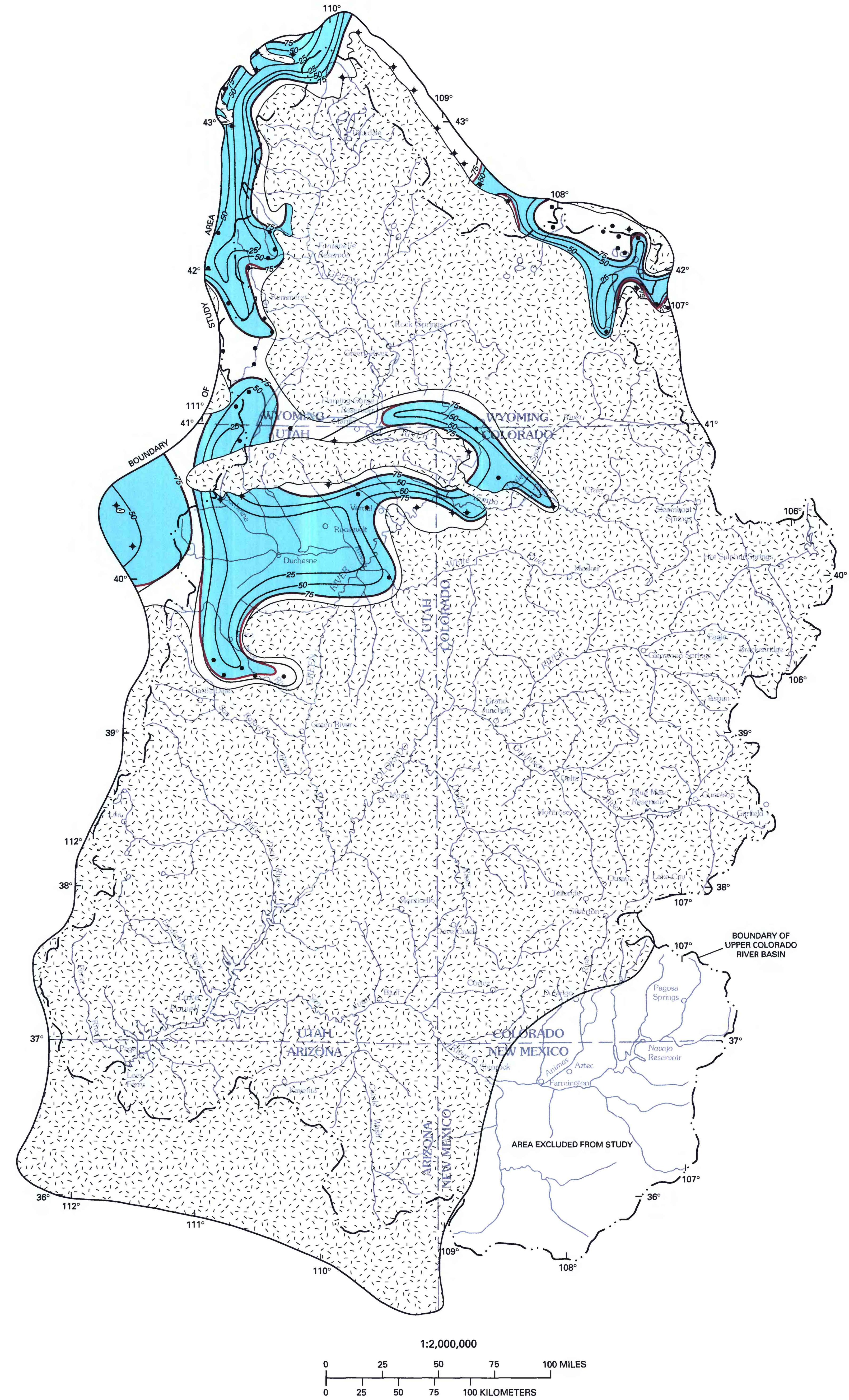



STRATIGRAPHIC NOMENCLATURE AND THICKNESS




LITHOLOGY

## EXPLANATION

- Area where Darwin-Humbug zone is missing because of erosion or nondeposition or thrust under Precambrian rocks
- ● Borehole with lithologic log used to prepare map
- ✦ Measured surface stratigraphic section used to prepare map

### Stratigraphic Nomenclature and Thickness

- Area where Darwin-Humbug zone crops out (generalized)
- —200— **Line of equal thickness**—Interval is 100 feet
- Approximate boundary between component geologic units

### Lithology

- Sandstone and shale with less than 25 percent limestone and dolomite interbeds
- Sandstone, shale, limestone, and dolomite; carbonate rocks commonly are brecciated. Anhydrite or gypsum present locally
- —25— **Line of equal percent sandstone**—Location generally is approximate because of sparse control. Interval is 25 percent
- Approximate boundary between lithofacies

Base from U.S. Geological Survey
U.S. base map, 1:2,500,000

# STRATIGRAPHIC NOMENCLATURE, THICKNESS, AND LITHOLOGY OF THE DARWIN-HUMBUG ZONE OF THE MADISON AQUIFER IN THE UPPER COLORADO RIVER BASIN AND VICINITY IN ARIZONA, COLORADO, NEW MEXICO, UTAH, AND WYOMING

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Arthur L. Geldon
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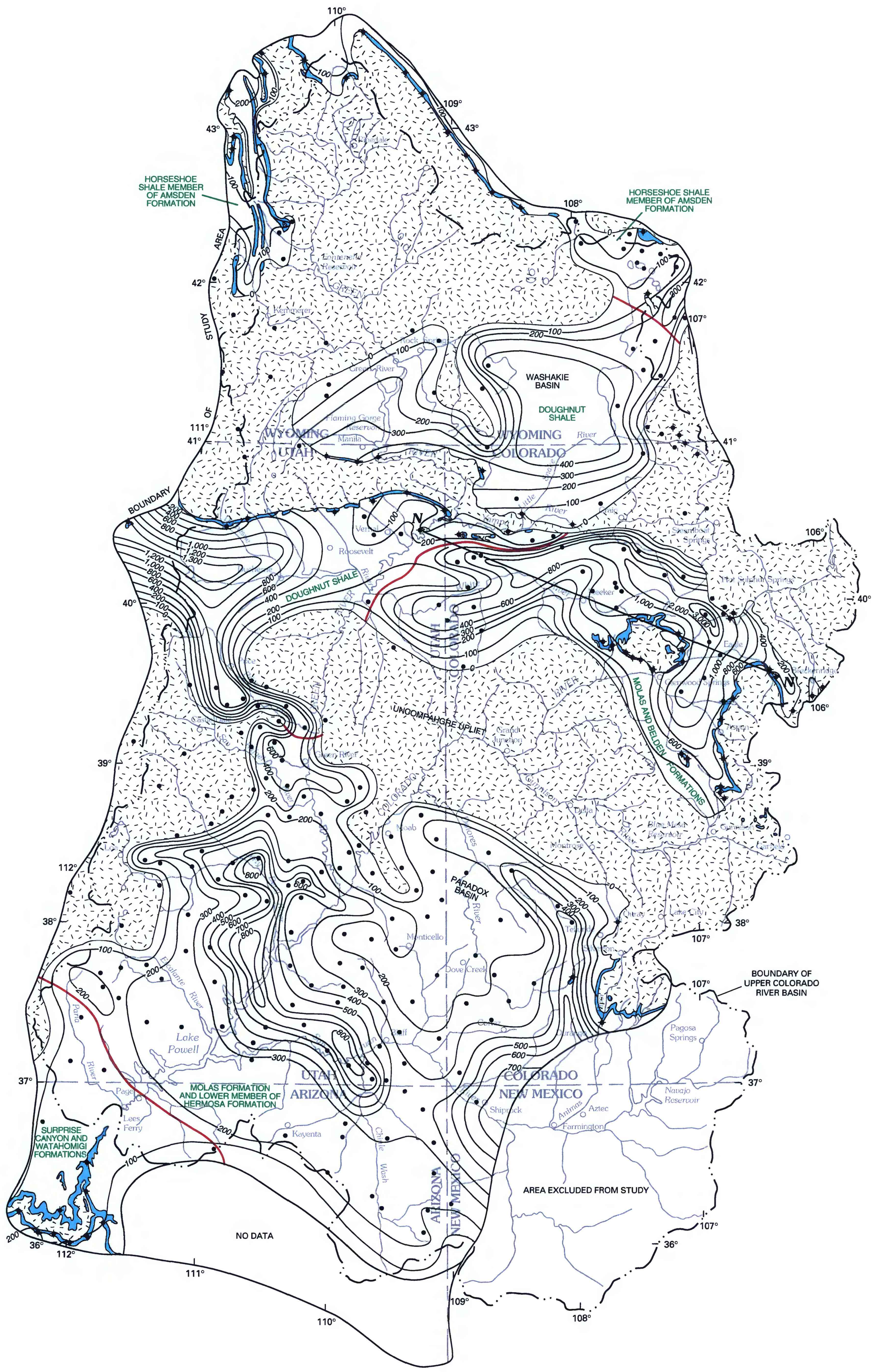
Geldon, A.L., 2002, Geology of Paleozoic rocks in the Upper Colorado River Basin in Arizona, Colorado, New Mexico, Utah, and Wyoming, excluding the San Juan Basin

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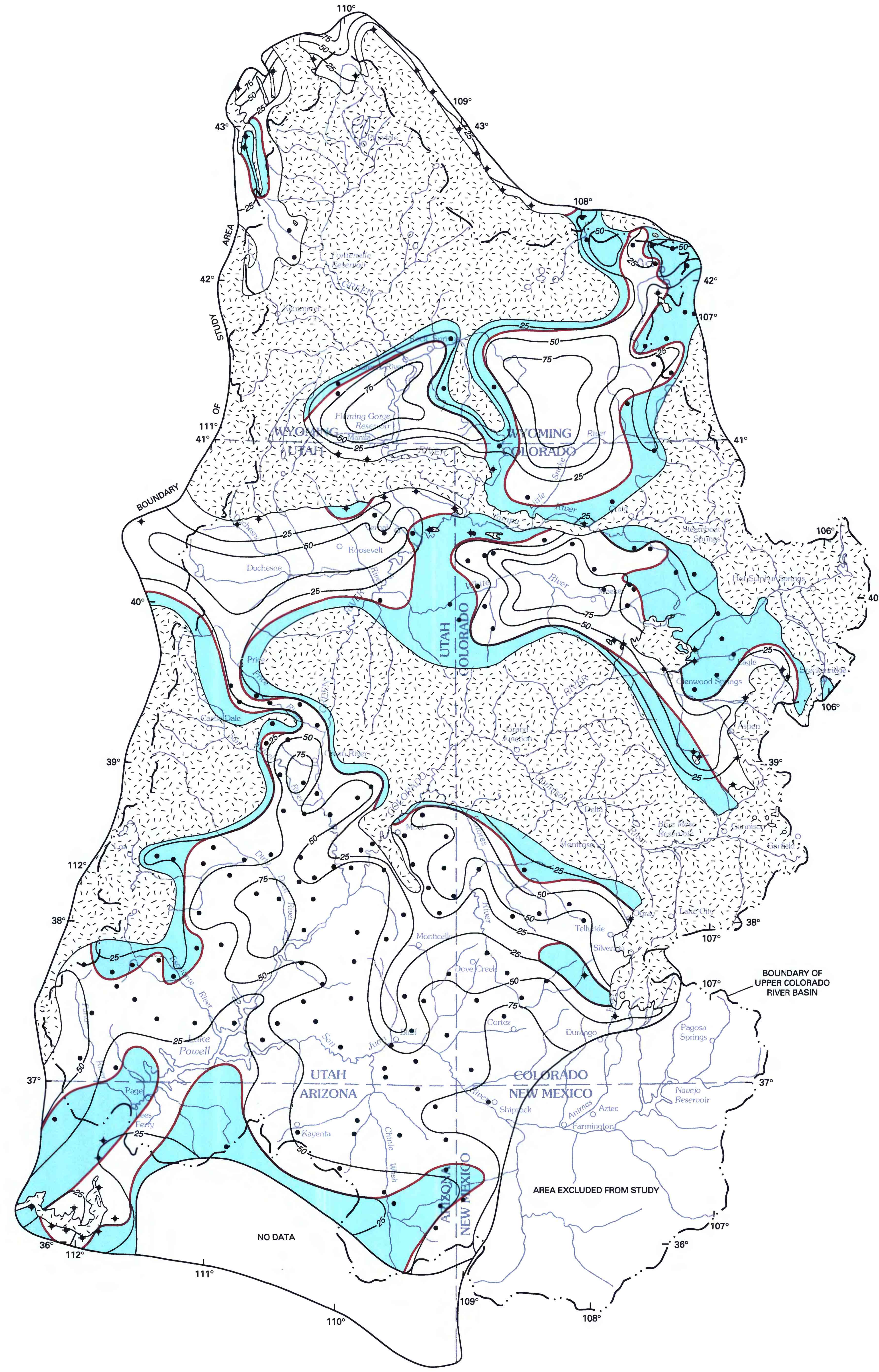
0 25 50 75 100 MILES

0 25 50 75 100 KILOMETERS

STRATIGRAPHIC NOMENCLATURE AND THICKNESS

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0 25 50 75 100 MILES

0 25 50 75 100 KILOMETERS

LITHOLOGY

## EXPLANATION

Area where Belden-Molas subunit is missing because of erosion or nondeposition or thrust under Precambrian rocks

• Borehole with lithologic log used to prepare map

✦ Measured surface stratigraphic section used to prepare map

### Stratigraphic Nomenclature and Thickness

Area where Belden-Molas subunit crops out (generalized)

—100— **Line of equal thickness**—Interval, in feet, is variable

Approximate boundary between component geologic units

N —— N′ Location of stratigraphic cross section shown in figure 24

### Lithology

Shale, limestone, and dolomite with less than 10 percent sandstone interbeds

Shale, limestone, dolomite, and sandstone

—50— **Line of equal percent limestone and dolomite**—Interval is 25 percent

Approximate boundary between lithofacies

Base from U.S. Geological Survey
U.S. base map, 1:2,500,000

# STRATIGRAPHIC NOMENCLATURE, THICKNESS, AND LITHOLOGY OF THE BELDEN-MOLAS SUBUNIT OF THE FOUR CORNERS CONFINING UNIT IN THE UPPER COLORADO RIVER BASIN AND VICINITY IN ARIZONA, COLORADO, NEW MEXICO, UTAH, AND WYOMING

By
Arthur L. Geldon
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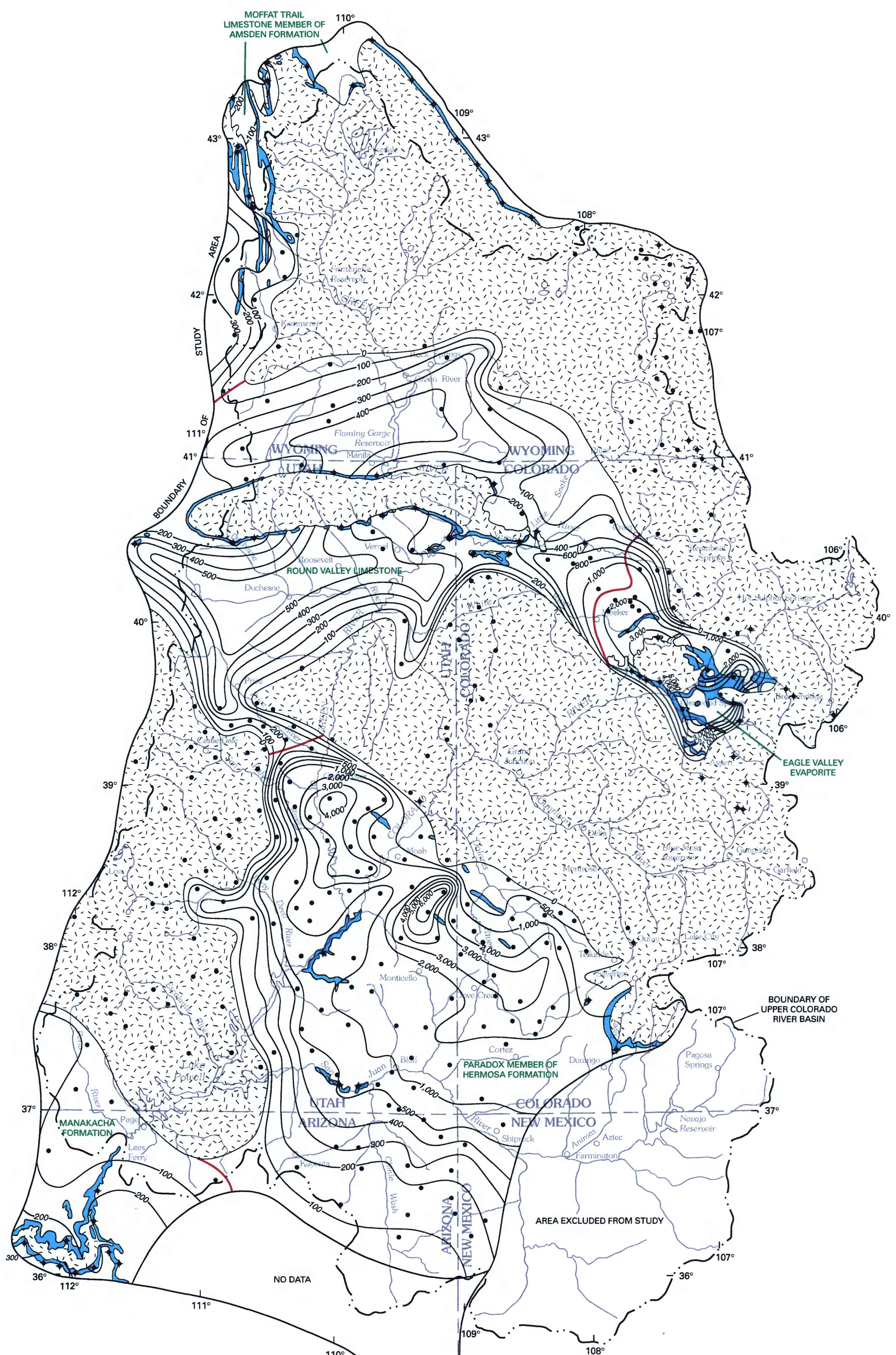


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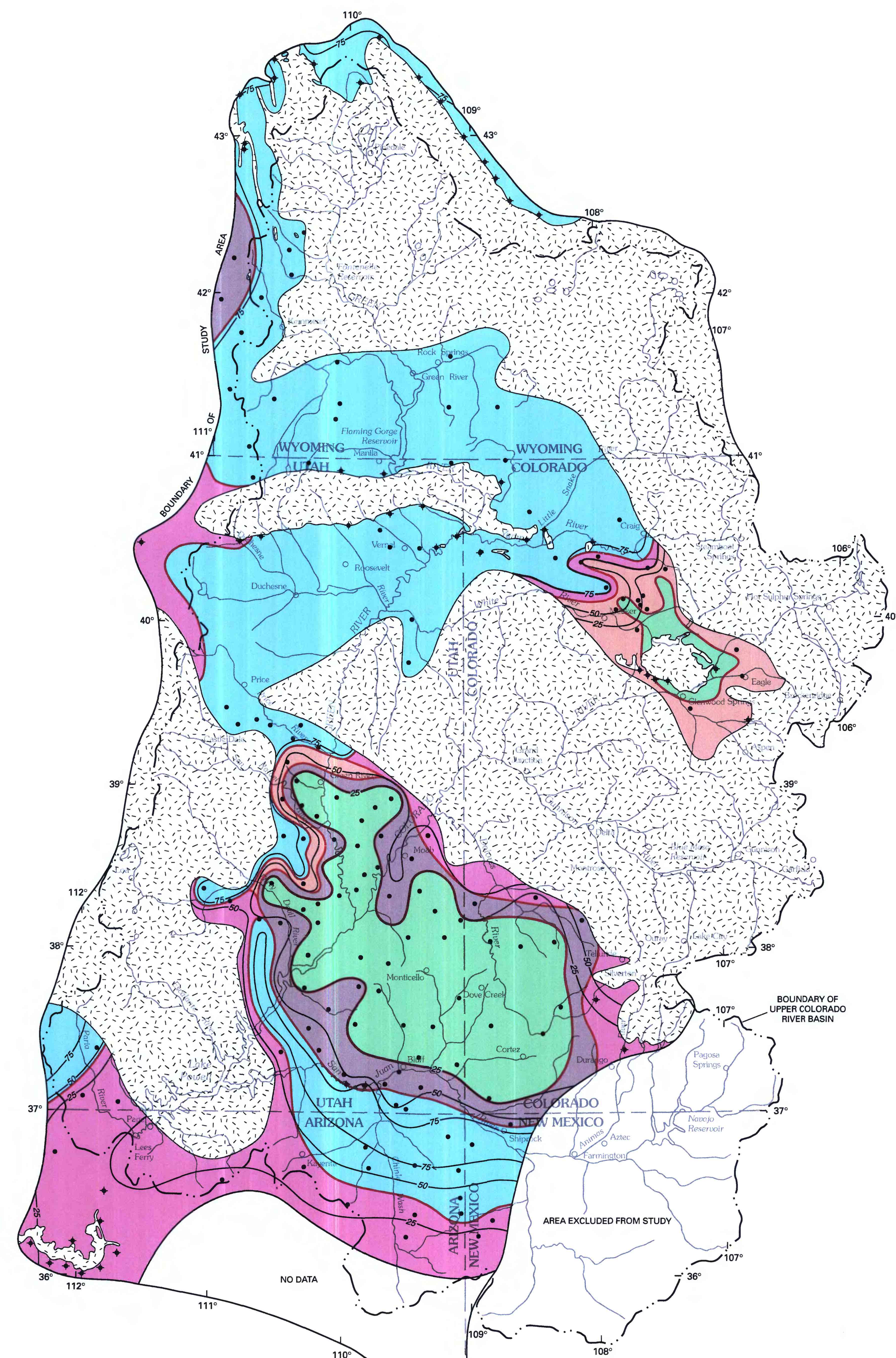
0 25 50 75 100 MILES

0 25 50 75 100 KILOMETERS

STRATIGRAPHIC NOMENCLATURE AND THICKNESS

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0 25 50 75 100 MILES

0 25 50 75 100 KILOMETERS

LITHOLOGY

## EXPLANATION

- Area where Paradox–Eagle Valley subunit is missing because of erosion or nondeposition
- • Borehole with lithologic log used to prepare map
- + Measured surface stratigraphic section used to prepare map

### Stratigraphic Nomenclature and Thickness

- Area where Paradox–Eagle Valley subunit crops out (generalized)
- —100— **Line of equal thickness**—Interval is 100 feet, except in centers of depositional areas of Eagle Valley Evaporite and Paradox Member of Hermosa Formation, where interval is 1,000 feet. Interval is variable south of Craig, Colorado. Small salt diapirs in the Paradox basin, where thicknesses reach 15,000 feet, are not shown because of scale
- Approximate boundary between component geologic units

### Lithology

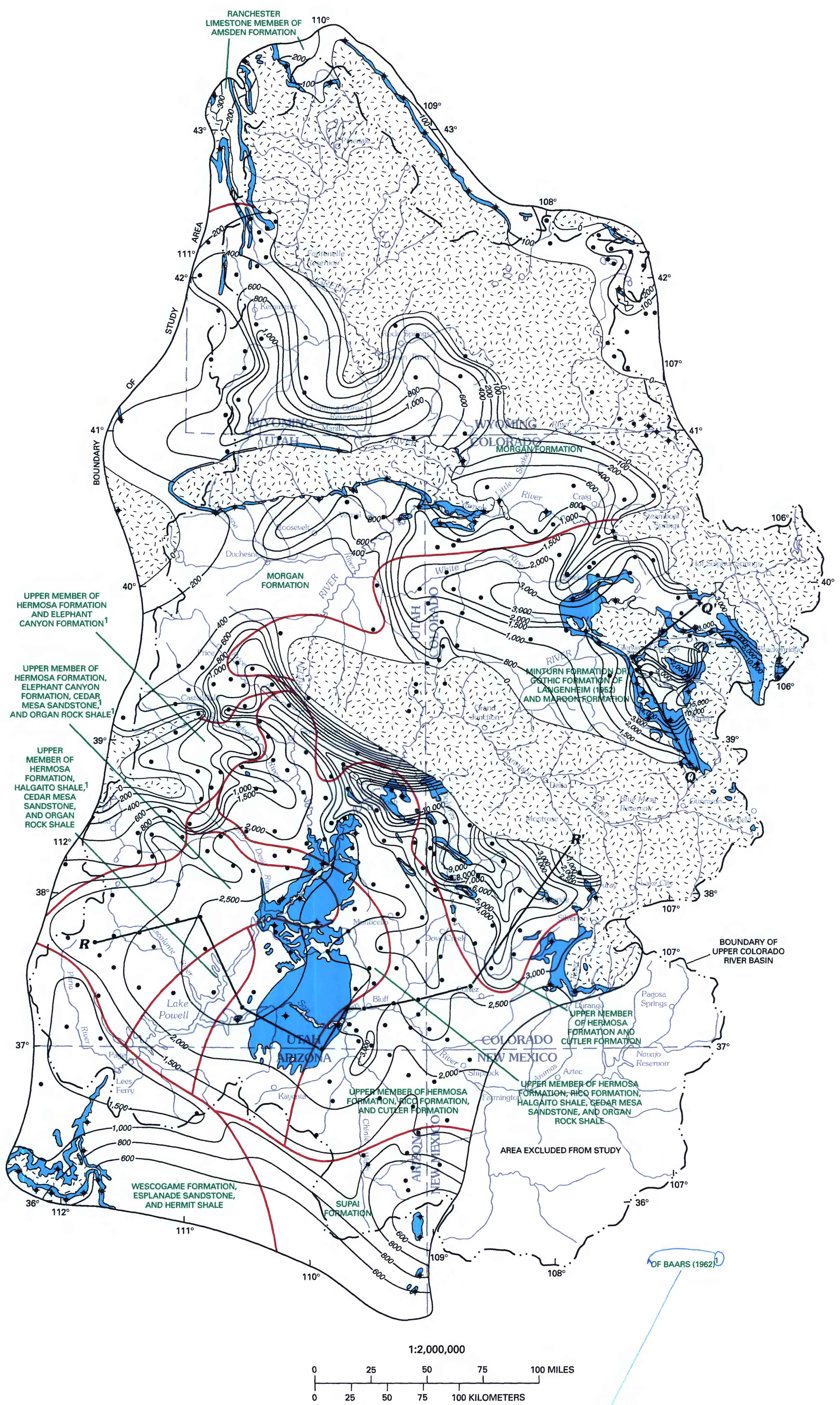
- Limestone, dolomite, and shale, with less than 10 percent sandstone and less than 5 percent anhydrite interbeds
- Limestone, dolomite, sandstone, and shale, with less than 5 percent anhydrite interbeds
- Limestone, dolomite, sandstone, shale, and anhydrite
- Limestone, dolomite, shale, and anhydrite, with less than 10 percent sandstone interbeds
- Anhydrite, gypsum, halite, and shale, with less than 25 percent sandstone, limestone, and dolomite interbeds
- —25— **Line of equal percent limestone and dolomite**—Interval is 25 percent
- Approximate boundary between lithofacies

Base from U.S. Geological Survey
U.S. base map, 1:2,500,000

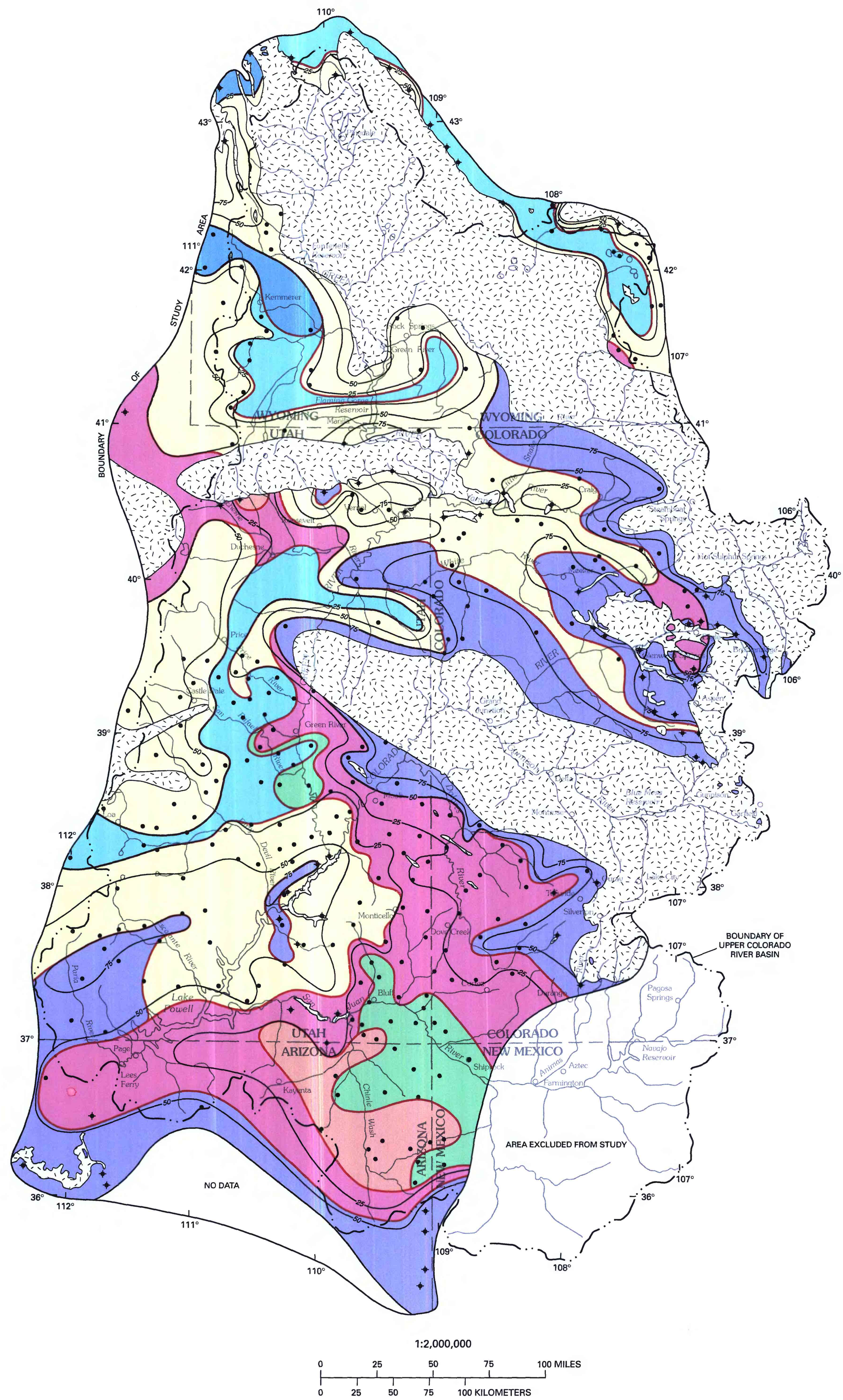
# STRATIGRAPHIC NOMENCLATURE, THICKNESS, AND LITHOLOGY OF THE PARADOX–EAGLE VALLEY SUBUNIT OF THE FOUR CORNERS CONFINING UNIT IN THE UPPER COLORADO RIVER BASIN AND VICINITY IN ARIZONA, COLORADO, NEW MEXICO, UTAH, AND WYOMING

By
Arthur L. Geldon
2002

Geldon, A.L., 2002, Geology of Paleozoic rocks in the Upper Colorado River Basin in Arizona, Colorado, New Mexico, Utah, and Wyoming, excluding the San Juan Basin




STRATIGRAPHIC NOMENCLATURE AND THICKNESS




LITHOLOGY

## EXPLANATION

- Area where Cutler-Maroon zone is missing because of erosion or non-deposition or is thrust under Precambrian rocks
- • Borehole with lithologic log used to prepare map
- ✦ Measured surface stratigraphic section used to prepare map

### Stratigraphic Nomenclature and Thickness

- Area where Cutler-Maroon zone crops out (generalized)
- —100— Line of equal thickness—Interval, in feet, is variable
- Approximate boundary between component geologic units
- R —— R′ Location of stratigraphic cross section shown in figures 34 and 37

### Lithology

- Sandstone and conglomerate with subordinate shale and less than 10 percent limestone and dolomite layers
- Shale with subordinate sandstone and less than 20 percent limestone and dolomite layers; may contain 1–16 percent gypsum and anhydrite
- Shale with less than 10 percent, each, sandstone and carbonate layers
- Shale with subordinate carbonate layers and less than 10 percent sandstone layers
- Limestone and dolomite with subordinate shale and less than 20 percent sandstone layers
- Limestone and dolomite with subordinate shale, less than 20 percent sandstone, and 5–20 percent anhydrite/gypsum layers
- Limestone, dolomite, sandstone, and shale
- —25— Line of equal percent sandstone and conglomerate—In some areas, location is approximate because of sparse control. Interval is 25 percent
- Approximate boundary between lithofacies

Base from U.S. Geological Survey
U.S. base map, 1:2,500,000

# STRATIGRAPHIC NOMENCLATURE, THICKNESS, AND LITHOLOGY OF THE CUTLER-MAROON ZONE OF THE CANYONLANDS AQUIFER IN THE UPPER COLORADO RIVER BASIN AND VICINITY IN ARIZONA, COLORADO, NEW MEXICO, UTAH, AND WYOMING

By
Arthur L. Geldon
2002

U.S. DEPARTMENT OF THE INTERIOR
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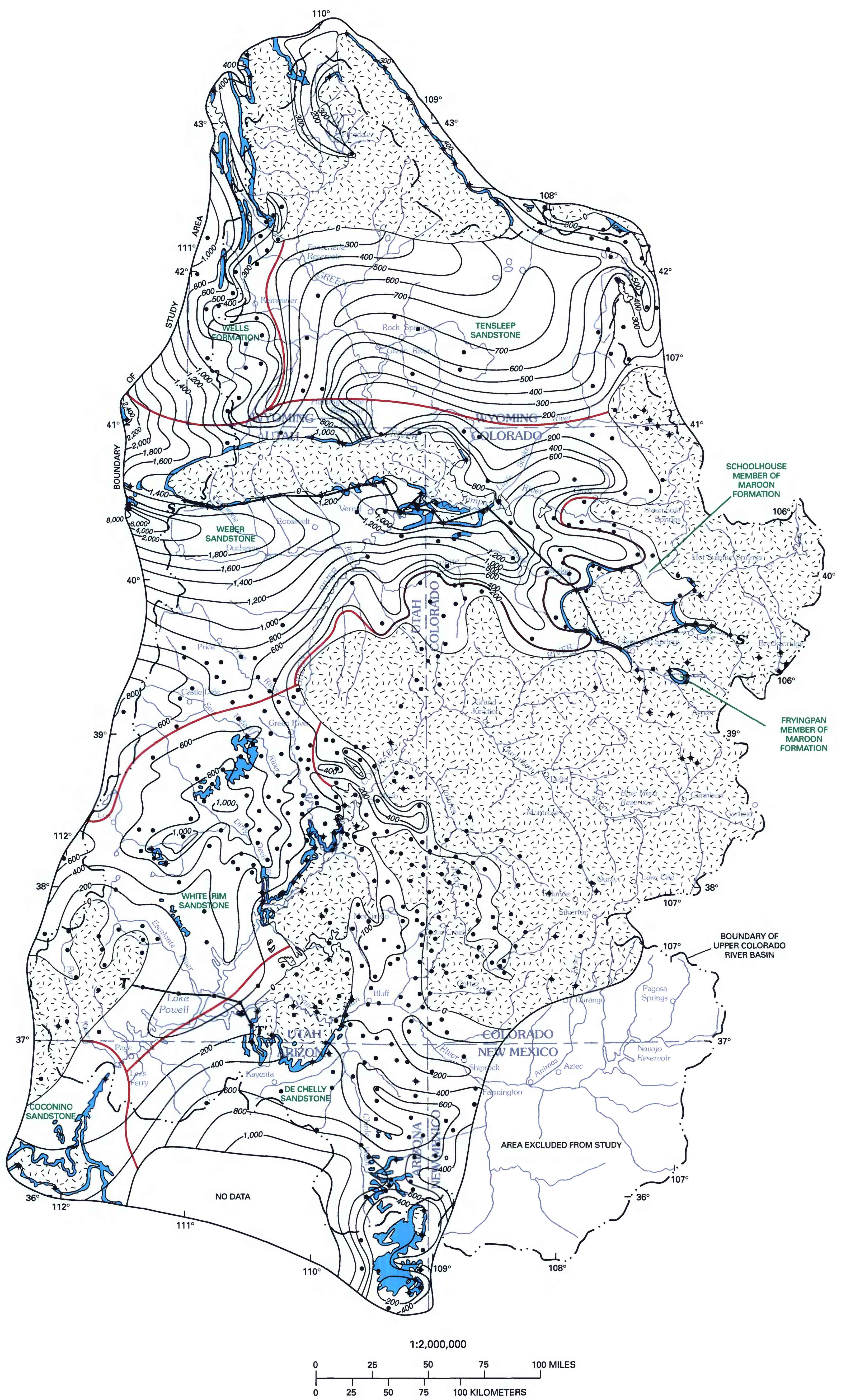
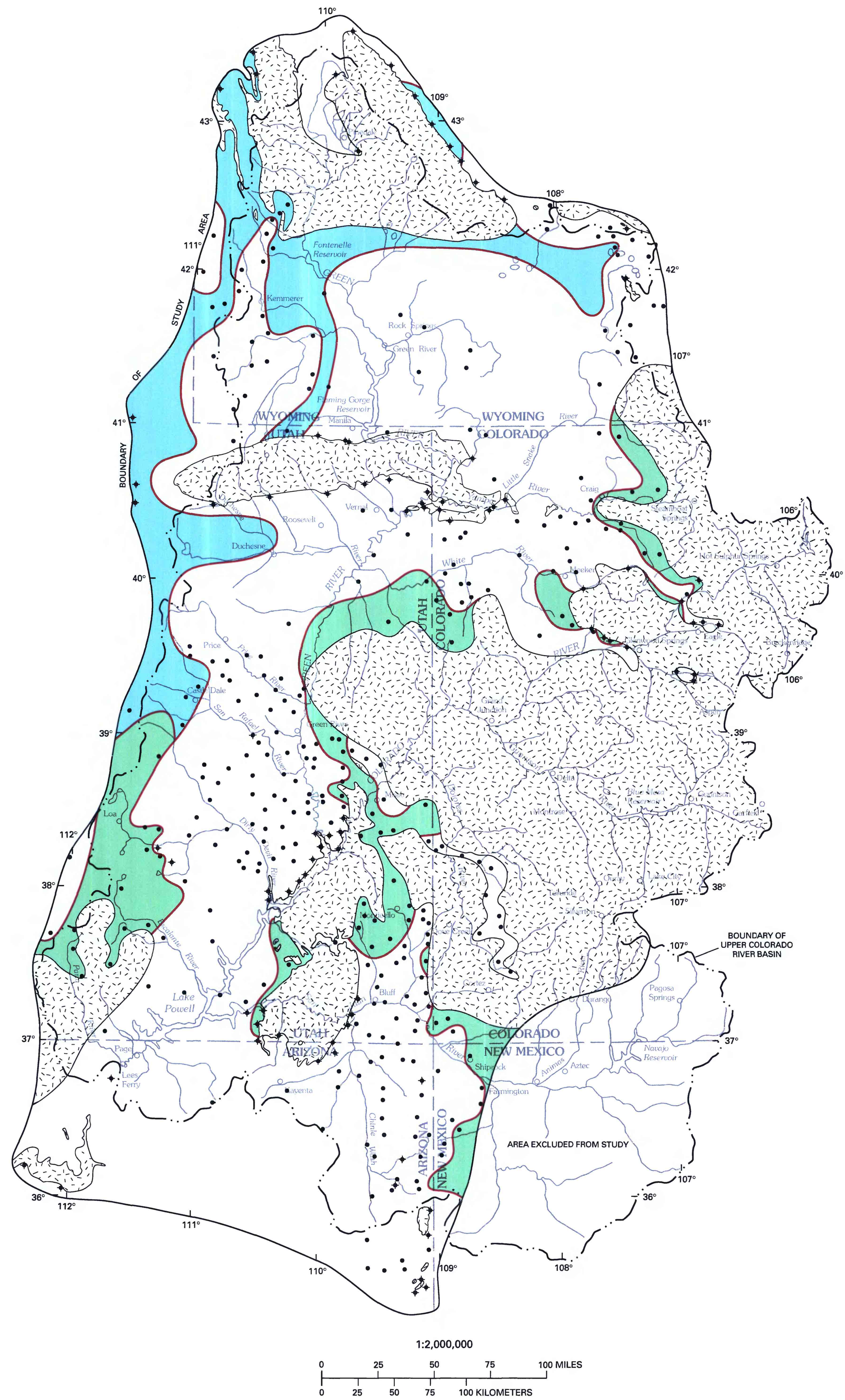
PROFESSIONAL PAPER 1411–A
Thickness and lithology of the Weber–De Chelly zone—PLATE 16
Geldon, A.L., 2002, Geology of Paleozoic rocks in the Upper Colorado River Basin in Arizona, Colorado, New Mexico, Utah, and Wyoming, excluding the San Juan Basin




STRATIGRAPHIC NOMENCLATURE AND THICKNESS




LITHOLOGY

## EXPLANATION

- Area where Weber–De Chelly zone is missing because of erosion or non-deposition or thrust under Precambrian rocks
- • Borehole with lithologic log used to prepare map
- + Measured surface stratigraphic section used to prepare map

**Stratigraphic Nomenclature and Thickness**

- Area where Weber–De Chelly zone crops out (generalized)
- —200— Line of equal thickness—Location is approximate in central Wyoming because of sparse control. Interval is 200 feet, except near Bluff, Utah, and in Wyoming, where interval is 100 feet, and in the Strawberry Valley area of Utah, where interval is 2,000 feet
- Approximate boundary between component geologic units
- T —— T′ Location of stratigraphic cross section shown in figures 44 and 45

**Lithology**

- Predominantly white, light-gray, tan, and orange quartz sandstone, with conglomerate layers and less than 10 percent shale, limestone, and dolomite
- Predominantly white, light-gray, tan, and orange quartz sandstone, with 10–30 percent shale interbeds
- Predominantly white, light-gray, tan, and orange quartz sandstone, with 10–30 percent limestone and dolomite interbeds
- Approximate boundary between lithofacies

Base from U.S. Geological Survey
U.S. base map, 1:2,500,000

# STRATIGRAPHIC NOMENCLATURE, THICKNESS, AND LITHOLOGY OF THE WEBER–DE CHELLY ZONE OF THE CANYONLANDS AQUIFER IN THE UPPER COLORADO RIVER BASIN AND VICINITY IN ARIZONA, COLORADO, NEW MEXICO, UTAH, AND WYOMING

By
Arthur L. Geldon
2002

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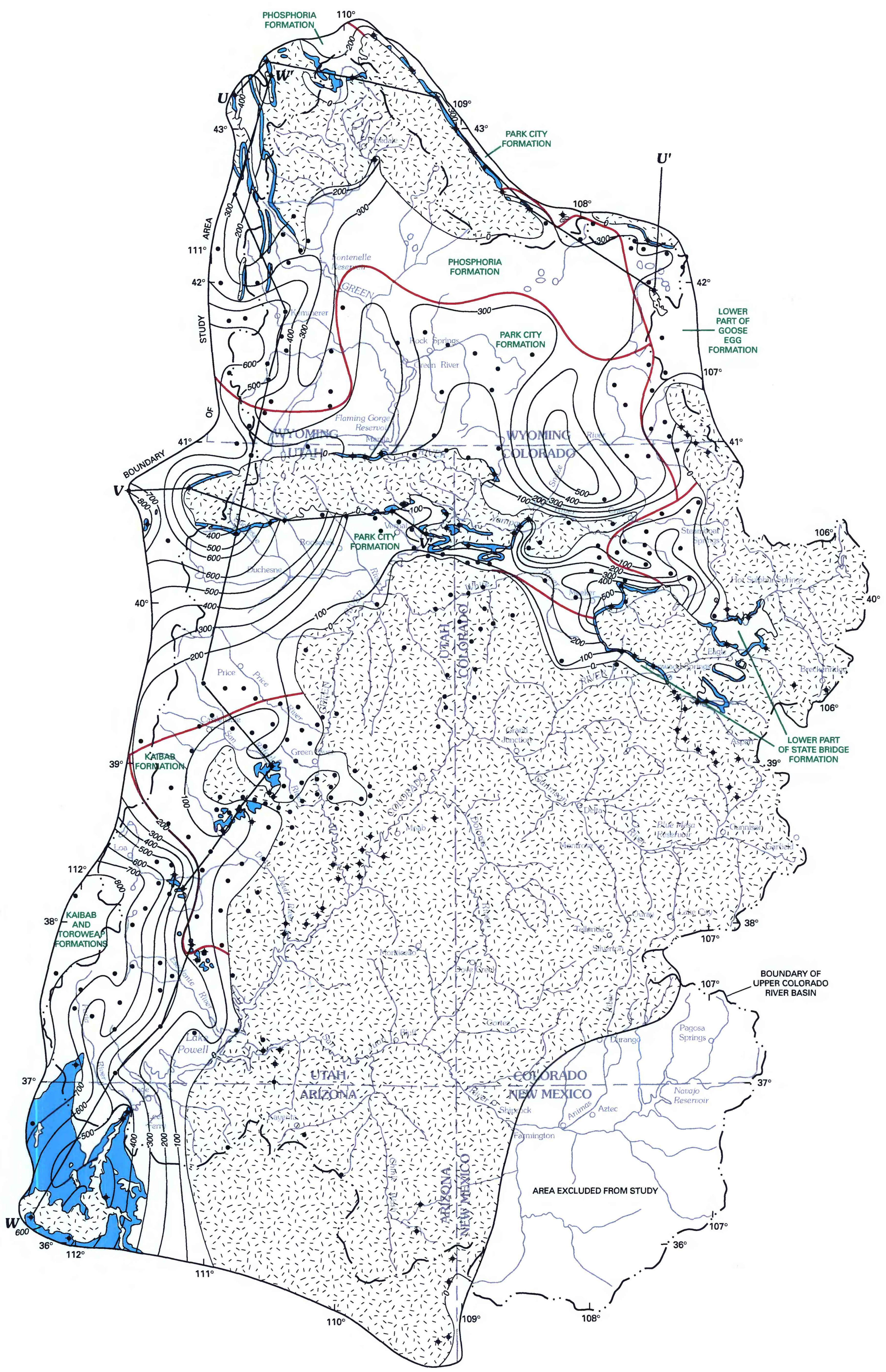
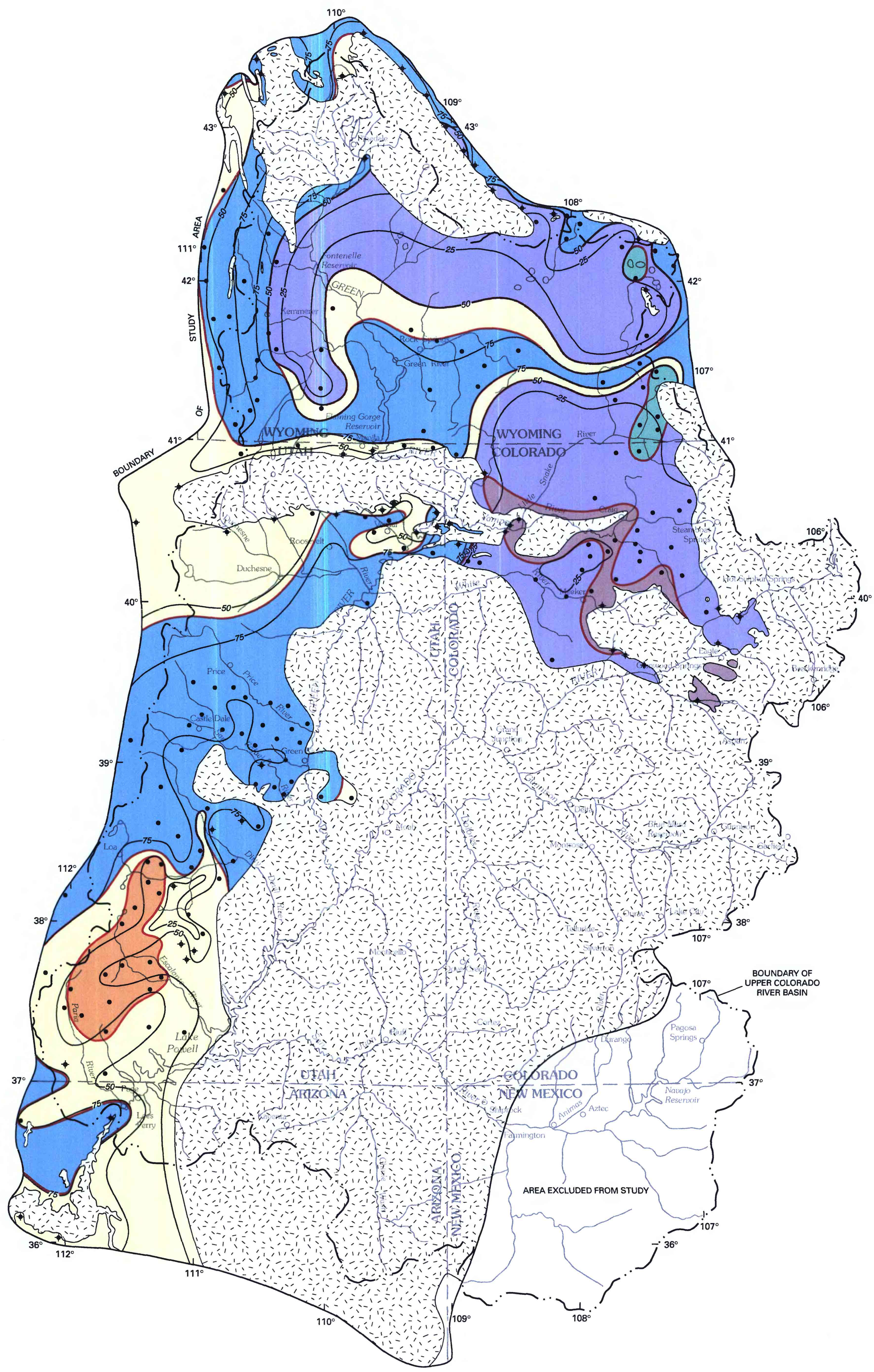



1:2,000,000

0 25 50 75 100 MILES

0 25 50 75 100 KILOMETERS

STRATIGRAPHIC NOMENCLATURE AND THICKNESS

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LITHOLOGY

## EXPLANATION

Area where Park City–State Bridge zone is missing because of erosion or nondeposition or is thrust under Precambrian rocks

● Borehole with lithologic log used to prepare map

✦ Measured surface stratigraphic section used to prepare map

### Stratigraphic Nomenclature and Thickness

Area where Park City–State Bridge zone crops out (generalized)

—200— Line of equal thickness—Interval is 100 feet

Approximate boundary between component geologic units

V——V' Location of stratigraphic cross section shown in figures 47, 49, and 50

### Lithology

Predominantly limestone and dolomite, with interbeds of chert, phosphorite, and shale and less than 10 percent, each, sandstone and anhydrite layers

Limestone, dolomite, and sandstone with chert, phosphorite, and shale interbeds

Limestone, dolomite, sandstone, and anhydrite (5–30 percent of unit), with typically less than 5 percent shale layers

Dark-gray, green, and red shale, with subordinate limestone and dolomite layers and less than 10 percent, each, sandstone and anhydrite layers

Sandstone and shale, with less than 10 percent limestone and dolomite

Predominantly red shale with 5–20 percent anhydrite layers and less than 30 percent dolomite layers

—50— Line of equal percent limestone, dolomite, chert, and phosphorite—Interval is 25 percent

Approximate boundary between lithofacies

Base from U.S. Geological Survey
U.S. base map, 1:2,500,000

# STRATIGRAPHIC NOMENCLATURE, THICKNESS, AND LITHOLOGY OF THE PARK CITY–STATE BRIDGE ZONE OF THE CANYONLANDS AQUIFER IN THE UPPER COLORADO RIVER BASIN AND VICINITY IN ARIZONA, COLORADO, NEW MEXICO, UTAH, AND WYOMING

By
Arthur L. Geldon
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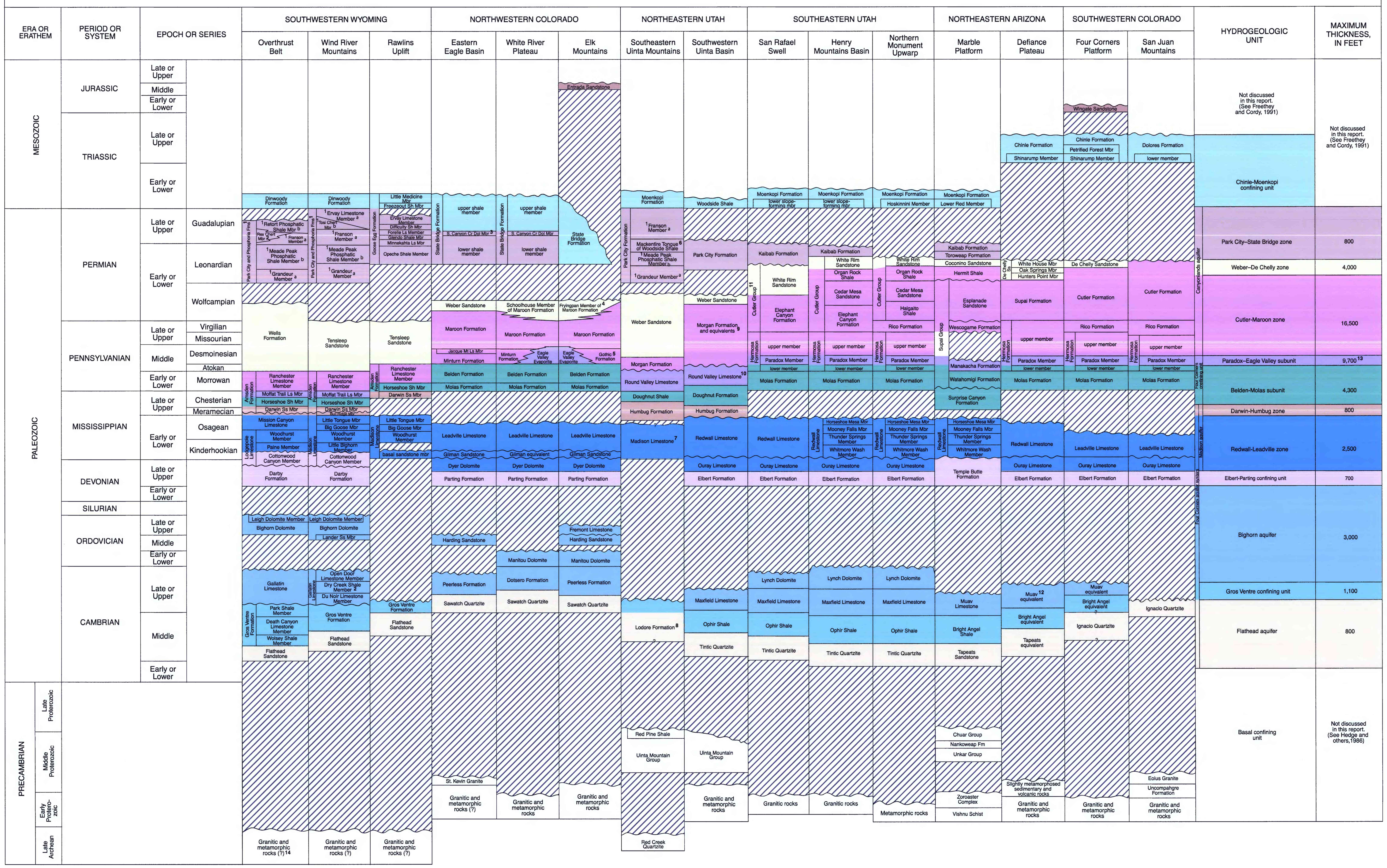
Table 1.—Generalized stratigraphic and hydrogeologic nomenclature of Precambrian, Paleozoic, and Mesozoic rocks in the Upper Colorado River Basin [only Mesozoic formations immediately overlying the Paleozoic rocks are listed. Abbreviations used in this table include: Fm = Formation; Mbr = Member; Ss = Sandstone; Ls = Limestone; Dol = Dolomite; Sh = Shale. Colors relate component geologic units to hydrogeologic units and are symbolic of the predominant lithology in the hydrogeologic unit: yellow and brown indicate sandstone and quartzite; shades of green indicate mostly shale; shades of blue indicate mostly carbonate rocks; other colors indicate mixed lithology. Contacts within series are generalized]




## FOOTNOTES

1. As suggested by McKelvey and others (1959), designation of the rocks of Park City/Phosphoria age as either "Park City Formation" or "Phosphoria Formation" is based on the predominant rock types, and each formation can include tongues of the other. Members of the Park City Formation are denoted by the letter a; members of the Phosphoria Formation are denoted by the letter b.

2. Of Shaw (1957); included in Open Door Limestone in some reports (for example, Keefer and Van Lieu, 1966).

3. Of Maughan (1980); also called South Canyon Creek Member (by Freeman, 1971, for example).

4. Of Johnson (1989); formerly considered a member of the State Bridge Formation (Freeman, 1971).

5. Of Langenheim (1952); also called "Minturn Formation."

6. The name "Mackentire Tongue of Woodside Shale," as used by McKelvey and others (1959), is applied to a sequence of red shale within the Park City Formation in the Uinta Mountains, even though the Woodside Shale generally is considered to be Triassic. Therefore, either the Mackentire Tongue is not a tongue of the Woodside Shale, or the Woodside Shale is partly Permian.

7. As indicated by Hallgarth (1959) and correlations made during this study, the lowermost beds of the Madison Limestone in the southeastern Uinta Mountains correlate with the uppermost beds of the Dyer Dolomite of northwestern Colorado. Therefore, either the uppermost Dyer Dolomite is Mississippian, as shown here, or the lowermost Madison Limestone in the southeastern Uinta Mountains is Late Devonian.

8. According to Untermann and Untermann (1954), fossils from the upper (shaly) part of the Lodore Formation where it crops out in the southeastern Uinta Mountains date the upper part of the Lodore Formation (an equivalent of the Gros Ventre Formation) as Late Cambrian. However, the lower part of the Lodore Formation (an equivalent of the Flathead Sandstone, Sawatch Quartzite, and Tintic Quartzite) is unfossiliferous. The age of the lower part of the Lodore Formation here is inferred to be Middle and Late Cambrian from its geographic position relative to equivalent quartzite/sandstone units. These formations range from Middle Cambrian on the north and west to Late Cambrian on the east.

9. Even though the Morgan Formation is considered to be Middle Pennsylvanian where it crops out in the Uinta Mountains (for example, Hansen and others, 1983), it can be traced southward in the subsurface into beds of the Elephant Canyon Formation of Baars (1962). Because the Elephant Canyon Formation is Early Permian where it crops out in the Monument Upwarp, both the Morgan and Elephant Canyon Formations must be Pennsylvanian and Permian in age where they merge (north of the San Rafael Swell).

10. The Round Valley Limestone correlates in the subsurface with the Eagle Valley Evaporite and the Paradox Member of the Hermosa Formation, both of which are Middle Pennsylvanian in age. Because the Round Valley Limestone where it crops out in the Uinta Mountains is Early Pennsylvanian, it is inferred to be time-transgressive in the subsurface. Hence, in the southwestern Uinta basin, where it merges with the Paradox Member, the Round Valley Limestone is interpreted to be Early and Middle Pennsylvanian. Similarly, the Doughnut Shale (Formation) is interpreted to be time-transgressive and is considered Late Mississippian and Early Pennsylvanian in the southwestern Uinta basin.

11. The Cutler Formation in southeastern Utah becomes divisible into several distinct units, to which the U.S. Geological Survey assigns member rank. Baars (1962), however, assigned these units formation rank and the Cutler, group rank, in southeastern Utah. A sequence of carbonate and clastic rocks that grades into the lowermost shaly beds of the Cutler was designated by Baars (1962) as the Elephant Canyon Formation. The nomenclature of Baars (1962) regarding the Cutler rocks is used in this report.

12. Cambrian units cropping out in the Grand Canyon, the Tapeats Sandstone, Bright Angel Shale, and Muav Limestone, were traced during this study into northeastern Arizona and southwestern Colorado by means of borehole lithologic logs. Because no names for the shale and carbonate units currently are recognized by the U.S. Geological Survey in Colorado, the names "Bright Angel equivalent" and "Muav equivalent" were used beyond the Grand Canyon area where rocks characteristic of the Bright Angel Shale and Muav Limestone, respectively, were identified. An equivalent of the Tapeats Sandstone crops out in the San Juan Mountains of Colorado, where it is called the Ignacio Quartzite. In this report, an axis of thinning in southwestern Colorado was considered the boundary between the extension of the Tapeats Sandstone beyond the Grand Canyon area, the "Tapeats equivalent," and the Ignacio Quartzite. As shown by Baars (1983, p. 54), the Cambrian geologic units become progressively younger from the Grand Canyon to the San Juan Mountains. Hence, in the Defiance Plateau and Four Corners platform columns, the ages of the Tapeats equivalent, Ignacio Quartzite, Bright Angel equivalent, and Muav equivalent are depicted as intermediate between ages in outcrop areas to the west and east.

13. Excluding salt diapirs of small areal extent that can be as much as 15,000 feet thick.

14. Although Precambrian rocks do not crop out and have not been penetrated by boreholes in the Overthrust Belt within the Upper Colorado River Basin, Archean granitic and metamorphic rocks are exposed in the Farmington complex, about 30 miles west of the Utah-Wyoming State line (Bryant, 1988).