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Geologic Framework of the San Juan Structural Basin of New Mexico, Colorado, Arizona, and Utah with Emphasis on Triassic through Tertiary Rocks

Regional Aquifer-System Analysis

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GEOLOGIC FRAMEWORK OF THE SAN JUAN STRUCTURAL BASIN OF NEW MEXICO, COLORADO, ARIZONA, AND UTAH, WITH EMPHASIS ON TRIASSIC THROUGH TERTIARY ROCKS

By STEVEN D. CRAIGG

REGIONAL AQUIFER-SYSTEM ANALYSIS—SAN JUAN BASIN, NEW MEXICO

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1420

U.S. DEPARTMENT OF THE INTERIOR

GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY

Charles G. Groat, Director

Reston, Virginia 2001

Library of Congress Cataloging in Publications Data

Craigg, Steven D.
Geologic framework of the San Juan structural basin of New Mexico, Colorado, Arizona, and Utah, with emphasis on Triassic through Tertiary rocks / by Steven D. Craigg.
p. cm. — (Regional aquifer-system analysis—San Juan Basin, New Mexico) (U.S. Geological Survey professional paper ; 1420)
Includes bibliographical references (p. -).
ISBN 0-607-88067-8
1. Geology, Stratigraphic—Mesozoic. 2. Geology, Stratigraphic—Teriary. 3. Geology—San Juan Basin (N.M. and Colo.) 4. San Juan Basin (N.M. and Colo.) I. Title. II. Series. III. Series : U.S. Geological Survey professional paper ; 1420.
QE675.C76 2000
557.89—dc20 95–37186
CIP

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FOREWORD

THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

The 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 an important component 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 in it 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

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(Plate is in pocket)

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Multiply	*By*	*To obtain*
inch	25.4	millimeter
foot	0.3048	meter
mile	1.609	kilometer
square mile	2.590	square kilometer

Sea level: In this report, "sea level" refers 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.

GEOLOGIC FRAMEWORK OF THE SAN JUAN STRUCTURAL BASIN OF NEW MEXICO, COLORADO, ARIZONA, AND UTAH, WITH EMPHASIS ON TRIASSIC THROUGH TERTIARY ROCKS

By STEVEN D. CRAIGG

ABSTRACT

The San Juan Basin is located in the Four Corners region of northwestern New Mexico and southwestern Colorado, with a smaller part in northeastern Arizona and southeastern Utah—an area of about 21,600 square miles. The basin is a structural depression formed during Laramide time with a maximum structural relief of about 10,000 feet. It contains about 14,400 feet of sedimentary rocks mainly ranging in age from Devonian through Tertiary.

The Regional Aquifer-System Analysis study area is slightly smaller than the San Juan structural basin, having an area of about 19,400 square miles, and is that part of the structural basin containing rocks of Triassic age and younger. This report describes the regional geologic and stratigraphic framework of the study area and includes detailed descriptions of the geologic units along with maps showing the thickness, depth to the top, and altitude and configuration of the top of the strata. The results presented in this report provide a hydrogeologic framework for the ground-water-flow modeling and water-quality studies of the San Juan Basin Regional Aquifer-System Analysis.

Triassic sedimentary rocks were generally deposited in continental (nonmarine) environments and collectively attain a maximum thickness of about 1,600 feet. The Chinle and Dolores Formations constitute the most important hydrogeologic units; regionally they could be considered confining units, but locally they are water yielding.

Jurassic rocks also mainly represent deposition in continental environments and collectively attain a maximum thickness of about 1,500 feet in the northwestern part of the basin. Although all these rocks locally yield some water to wells, the Westwater Canyon Member of the Morrison Formation is regionally the most important aquifer.

Cretaceous sedimentary rocks represent continental, marginal marine, and marine environments associated with transgressing and regressing seas. During Cretaceous time, at least 6,500 feet of strata were deposited. Regionally, the Dakota and Gallup Sandstones are important water-yielding formations, although other units also yield dependable local supplies of water.

Tertiary sedimentary rocks were deposited in continental environments and attain a maximum thickness of about 3,800 feet. The Ojo Alamo Sandstone and San Jose Formation are the most important hydrogeologic units.

Maps showing depth of the top, altitude, configuration of the top, and, if possible, thickness of the major formations were prepared from a data base of about 24,000 oil- and gas-test wells in the basin using a surface-contour-generating software package interfaced with a Geographic Information System. These maps were used as input to a digital, three-dimensional ground-water-flow model of the regional aquifer system in the basin.

INTRODUCTION

This report is a result of the U.S. Geological Survey's Regional Aquifer-System Analysis (RASA) study of the San Juan structural basin, a project that began in October 1984. The objectives of the San Juan Basin RASA are to: (1) define and evaluate the ground-water system; (2) assess the effects of past, present, and potential ground-water use on aquifers and streams; and (3) determine the availability and quality of ground water (Welder, 1986).

PURPOSE AND SCOPE

This report identifies and defines the regional geologic and stratigraphic framework, and the extent and geologic characteristics of Triassic through Tertiary sedimentary rocks in the study area. Data used in this report were collected during the study or were derived from existing records in the U.S. Geological Survey's computerized National Water Information System (NWIS) data base and the Petroleum Information Corporation's data base.

LOCATION AND GEOGRAPHIC SETTING

The San Juan structural basin encompasses parts of New Mexico, Colorado, Arizona, and Utah and has an area of about 21,600 square miles (fig. 1). The structural basin is about 140 miles wide and 200 miles long. The study area is that part of the structural basin that contains rocks of Triassic or younger age and, therefore, is less extensive than the structural basin. It is about 140 miles wide (about the same as the structural basin), 180 miles long, and has an area of about 19,400 square miles. Triassic through Tertiary sedimentary rocks are emphasized in this study because they are the principal aquifers and confining units in the basin.

Altitudes in the study area range from about 4,500 feet above sea level in southeastern Utah to about 11,000 feet in the southeastern part of the basin. Annual precipitation in the mountainous areas along the northern and eastern margins of the basin is 20–30 inches; annual precipitation in the lower, central part of the basin generally is less than 8 inches (Craigg and others, 1989). Mean annual precipitation in the study area is about 12 inches.

Data obtained from the U.S. Bureau of the Census (1980, 1985) were used to estimate the population of the study area. The population in 1970 was estimated to be about 134,000. The population increased to about 194,000 by 1980, 212,000 by 1982, 221,000 by 1984, and then decreased to about 210,000 in 1985. The economy of the basin is supported by exploration and mining of uranium, coal, and oil and gas; urban enterprise; farming and ranching; tourism; and recreation. The fluctuation in population was related to changes in the economic strength of the minerals and oil and gas industries, and their support services. Uranium mining and milling increased rapidly until the late 1970's, when most uranium-mining activity ended in the study area. Likewise, the oil and gas industry prospered until about 1983 and then decreased rapidly, also affecting many jobs in support industries.

PREVIOUS INVESTIGATIONS

Numerous geologic investigations have been made in the San Juan structural basin, mainly because of its wealth of energy resources but also because of academic interest—the area is a classic example of basin structural evolution that is somewhat penecontemporaneous with basin sedimentary deposition. Numerous hydrologic investigations also have been made in this basin; many of them relate to the evaluation of ground-water resources for Indian tribes, public-land management agencies, and municipalities, as well as the determination of potential effects of various energy-development plans on water resources. It is beyond the scope of this report to list all these works. Many of the major reports, however, are listed in the Selected References section; some of the major references for structure, stratigraphy, and hydrogeology are listed in this section; and other references are given throughout the text. For a comprehensive listing, Wright (1979) compiled an extensive bibliography of San Juan Basin geologic and hydrologic literature.

Dutton (1885) was among the first geologists to visit the San Juan Basin, where he made a geologic reconnaissance of the area. His study of Mount Taylor and the Zuni Plateau was published in the now-classic Sixth Annual Report of the U.S. Geological Survey. The general structure of the basin was discussed in an early New Mexico Geological Society field-trip guidebook by Kelley (1951). Hunt and Dane (1954), Baltz (1967), and Woodward (1974, 1987) also discussed structure and tectonics of the basin.

Geologic maps of the San Juan Basin area are available at a scale of 1:500,000 for each of the States in the study area: Dane and Bachman (1965) for New Mexico, Wilson and others (1969) for Arizona, Tweto (1979) for Colorado, and Hintze (1981) for Utah. These State geologic maps were used in compiling the geologic map of the study area for this report (pl. 1). The geology of the 1° x 2° (scale 1:250,000) quadrangles that cover the area has been determined and the maps are listed in the Selected References section of this paper. Numerous 7.5-minute quadrangles (scale 1:24,000) of the basin also are widely available; only those maps specifically referred to in the text are listed in the Selected References. In addition, Woodward (1987) compiled results of comprehensive geologic investigations along the eastern boundary of the San Juan Basin and adjacent areas.

Although not discussed specifically in this report, Precambrian and Paleozoic rocks in the basin are detailed in the following major works:

Precambrian: Cross and Purington (1899), Cross and others (1899, 1905a, b), Wood and Northrop (1946), Kelley (1950), Fitzsimmons (1963, 1967), and Woodward (1987).

Cambrian: *Ignacio Quartzite*—Cross and others (1899), Barnes (1954), and Rhodes and Fisher (1957).

Devonian: *Aneth Formation*—Knight and Cooper (1955); *Elbert Formation*—Knight and Cooper (1955) and

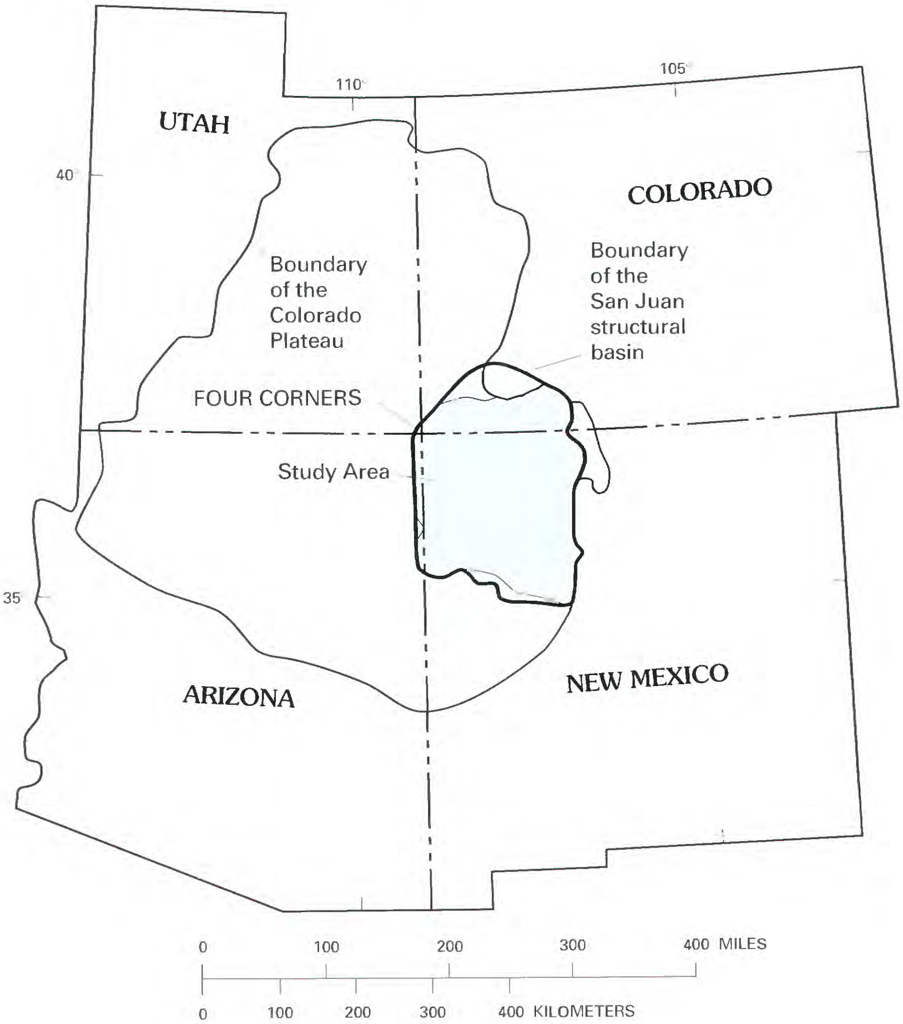


FIGURE 1.—Location of the Regional Aquifer-System Analysis study area in the San Juan structural basin, New Mexico, Colorado, Arizona, and Utah.

Rhodes and Fisher (1957); *Ouray Limestone*—Cross and others (1899), Burbank (1941), and Knight and Baars (1957).

Mississippian: *Leadville Limestone*—Emmons and others (1894) and Burbank (1941).

Pennsylvanian: *Molas Formation*—Cross and others (1905a, b) and Wengerd and Matheny (1958); *Madera Formation*—Read and others (1944) and Kelley and Wood (1946); *Hermosa Formation*—Cross and others (1899), Bass (1944), and Wengerd and Matheny (1958); *Honaker Trail Formation*—Wengerd and Matheny (1958); *Paradox Formation*—Bass (1944) and Wengerd and Matheny (1958); *Pinkerton Trail Formation*—Wengerd and Matheny (1958).

Permian: *Abo Formation*—Needham and Bates (1943), Kelley and Wood (1946), and Wood and Northrop (1946); *Cutler Formation*—Cross and others (1905 a, b), Baker and Reeside (1929), and Wengerd and Matheny (1958); *De Chelly Sandstone*—Gregory (1916); *Yeso Formation*—Needham and Bates (1943), Kelley and Wood (1946), and Wood and Northrop (1946); *Glorieta Sandstone*—Needham and Bates (1943); *San Andres Limestone*—Needham and Bates (1943) and McKee and others (1959). In addition, Baars (1962) provided a comprehensive general reference for Permian rocks of the Colorado Plateau.

Major references for Triassic strata include Cross and others (1899), who named the Dolores Formation; Ward (1901), who named the Moenkopi Formation; and Gregory (1917), who named the Chinle Formation. Repenning and others (1969) also reported in detail on the stratigraphy of the Moenkopi and Chinle Formations, as did Stewart and others (1972a, b).

The stratigraphy of various Jurassic rocks in the basin was the subject of Emmons and others (1894), in which the Morrison Formation was named by G.H. Eldridge; Cross and others (1899), who conducted early investigations in southwestern Colorado; Gilluly and Reeside (1928), who named the Entrada Sandstone; Burbank (1930), who first named the Wanakah Formation; and Baker and others (1936, 1947), who made regional correlations of Jurassic units throughout the Four Corners area. Craig and others (1955) conducted important work on the stratigraphy and uranium deposits of the Morrison in the Colorado Plateau. Other works concentrating on Jurassic rocks include Goldman and Spencer (1941), Harshbarger and others (1951), Smith (1953), and Green and Pierson (1977). Recent changes in nomenclature of certain Jurassic rocks have been made by Condon and Peterson (1986), Condon and Huffman (1988), and Condon (1989a, b).

Major investigations of Cretaceous rocks have been made by Holmes (1877), who named the Pictured Cliffs Sandstone; Cross and Purington (1899), who named the Mancos and Lewis Shales; Bauer (1916), who named the Kirtland Shale and Fruitland Formation; Collier (1919), who named the three-part Mesaverde Formation (now Mesaverde Group); and Sears (1925), who named the Gallup Sandstone. Sears and others (1936) defined the stratigraphy and coal resources of Cretaceous rocks in the southern part of the basin. Sears and others (1941) is a major work that established the concept of sediment balance in a subsiding basin as a major factor controlling transgression-regression of a sea. More recent work on Cretaceous rocks has included publications by Fassett and Hinds (1971) on the Fruitland Formation, Owen (1973) and Owen and Siemers (1977) on the Dakota Sandstone, and Molenaar (1973, 1974, 1977b) on the Gallup Sandstone.

Investigations that have defined rocks of Tertiary age include those by Emmons and others (1894), in which the Animas Formation was named by Whitman Cross; Keyes (1906), who named the Nacimiento Formation; Brown (1910), who named the Ojo Alamo Sandstone; and Gregory (1916), who named the Chuska Sandstone. Simpson (1948a, b) named the San Jose Formation, which later was subdivided by Baltz (1967). The Ojo Alamo Sandstone has more recently been investigated in detail by O'Sullivan and others (1972), Powell (1973), and Fassett (1974).

Some of the hydrologic investigations made in the San Juan Basin include those by Gregory (1916), who conducted a geographic and hydrographic reconnaissance of the Navajo Indian Reservation and adjacent areas, and Renick (1931), who conducted a ground-water investigation of the southeastern part of the basin. Irwin (1966) investigated ground-water resources of the Ute Mountain Ute Indian Reservation in Colorado and New Mexico; Baltz and West (1967) investigated ground-water resources of the Jicarilla Apache Reservation in New Mexico; and Cooley and others (1969) conducted a regional hydrologic investigation of the Navajo and Hopi Indian Reservations in Arizona, New Mexico, and Utah. Ground-water investigations in the southern part of the San Juan Basin include those by Gordon (1961), Cooper and John (1968), Mercer and Cooper (1970), Shomaker (1971a), and Risser and Lyford (1983). Stone and others (1983) published the results of a regional hydrogeologic investigation of the New Mexico part of the San Juan Basin. Master's theses that cover selected 15-minute quadrangles in the basin were done by Brown (1976), Anderholm (1979), Brod (1979), and Craigg (1980). Craigg (1992) conducted a ground- and surface-water investigation of the Jemez, Zia, and Santa Ana Pueblos in the southeastern part of the basin. The San Juan Basin RASA staff has prepared U.S. Geological Survey Hydrologic Investigations Atlases (HA–720–A through J) for 10 major aquifers in the basin; included are Craigg and others (1989, 1990); Kernodle and others (1989, 1990); Dam and others (1990a, b); Levings and others (1990a, b); and Thorn and others (1990a, b).

ACKNOWLEDGMENTS

The author expresses appreciation to the following U.S. Geological Survey geoscientists in Denver, Colo., for providing useful discussion, ideas, review comments, timely stratigraphic information, and recent or pending nomenclature changes for various geologic units: S.M. Condon, J.E. Fassett, A.C. Huffman, Jr., and C.M. Molenaar; Vickie L. Clark deserves special thanks for providing access to computer facilities. Also, I am indebted to J.M. Kernodle (U.S. Geological Survey, Albuquerque, N. Mex.) for his expertise and assistance with Geographic Information Systems.

REGIONAL GEOLOGIC SETTING

The San Juan structural basin is an approximately circular, asymmetric structural depression located primarily in the east-central part of the Colorado Plateau (fig. 1). The basin is one of several large structural basins underlying the Colorado Plateau. The San Juan Basin straddles the Four Corners area but mainly is located in northwestern New Mexico and southwestern Colorado; smaller parts are located in northeastern Arizona and southeastern Utah (figs. 1 and 2). The basin is about 140 miles wide, 200 miles long, and has an area of about 21,600 square miles. Faulting is common, especially in the northeastern, southeastern, and south-central parts of the basin, and also along the north-central and east-central margins (pl. 1).

TECTONIC EVOLUTION

The tectonic evolution of the San Juan Basin is extensive and complex. The Precambrian geologic history of the region is obscured by complex metamorphism, deformation, intense erosion, and subsequent burial under Phanerozoic rocks; Kelley (1950, p. 101) reported that there is no evi-

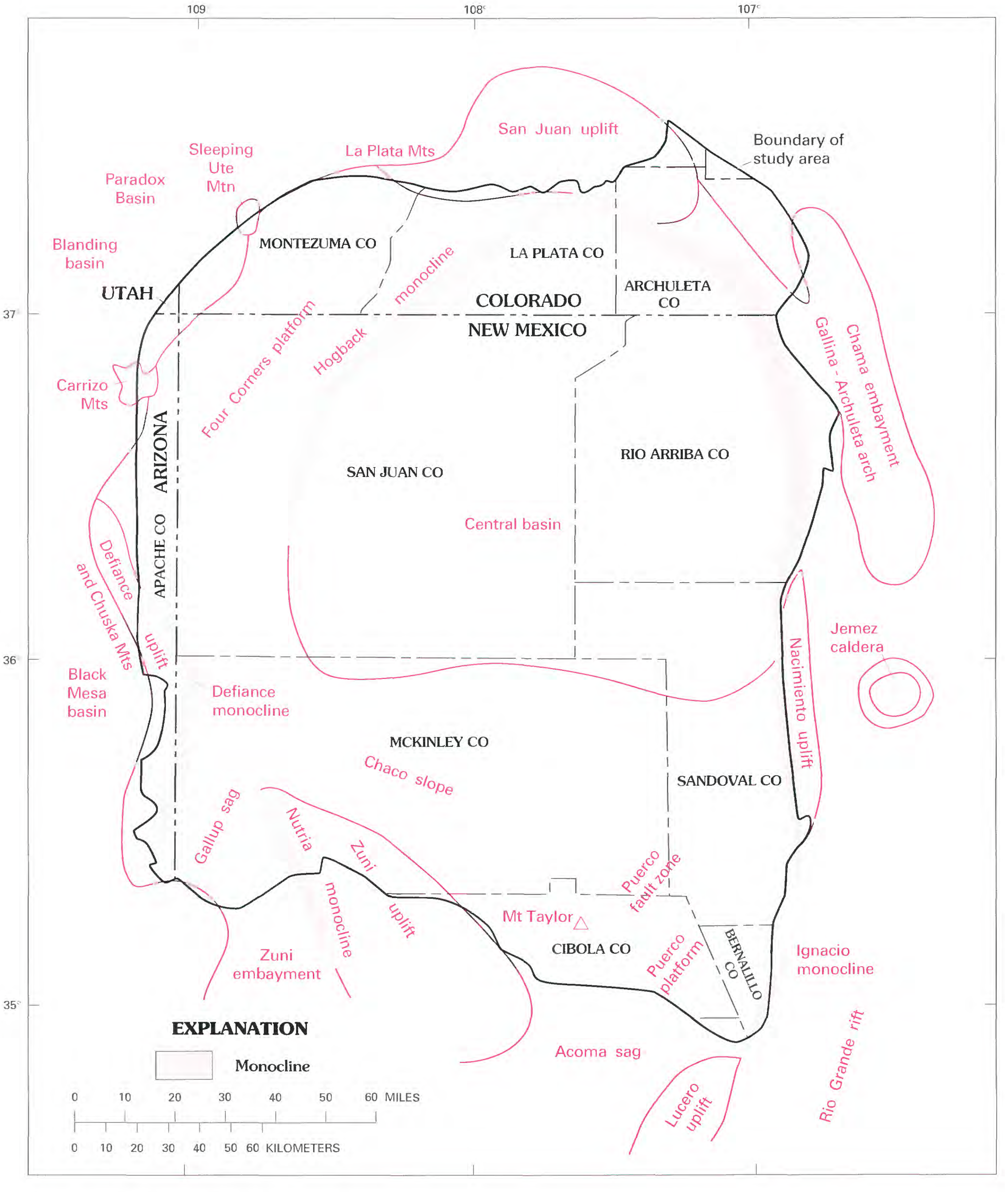


FIGURE 2.—Structural features of the San Juan Basin and adjacent areas. Modified from Kelly (1951).

dence to indicate any structural depression during Precambrian time in the present San Juan Basin area.

Tectonism began during late Paleozoic time along the areas bordering the present basin (San Juan Uplift in the north, Nacimiento Uplift in the east, Zuni Uplift in the south, and Defiance Uplift in the west; fig. 2). Recurrent uplift and minor deformation continued throughout Mesozoic time (Kelley, 1951, p. 129).

As noted by Kelley (1950, 1951, 1957), it was not until latest Late Cretaceous and early Tertiary time that the principal structural elements of the present San Juan Basin began to form. The San Juan Basin is, therefore, predominantly a Laramide feature. After the culmination of the Laramide orogeny, minor doming associated with intrusion by laccoliths and other igneous bodies during middle and late Tertiary time modified some of the older structures and reactivated faults in the southeastern part of the basin (Woodward and Callender, 1977, p. 209).

STRUCTURAL BOUNDARIES AND OTHER MAJOR STRUCTURAL ELEMENTS

Major structural elements of the San Juan Basin were first delineated by Kelley (1950), with minor later revisions by Kelley (1951, 1957, 1963), Kelley and Clinton (1960), Baltz (1967), and Woodward and Callender (1977). Structural boundaries are distinct and well defined in many areas, whereas in other areas the basin merges transitionally into adjacent structural depressions or uplifts. Numerous small structural embayments or sags extend from the San Juan Basin proper into adjacent areas (fig. 2) (Kelley, 1950, p. 101).

Structural boundaries and elements of the San Juan Basin are of three major types: (1) large, elongated, domal uplifts; (2) low, marginal platforms; and (3) abrupt monoclines. The following discussion of these features is summarized mainly from the works of Kelley (1950, 1951, 1957) and Woodward (1987).

STRUCTURAL BOUNDARIES

Along the northern margin, the San Juan Basin is bounded by the San Juan Uplift (figs. 2, 3*A*, and 3*B*), with its Precambrian core of crystalline rocks rising abruptly from the basin rim. The San Juan Uplift is a northwest-trending feature about 75 miles long and 35 miles wide. Structural relief between the uplift and the San Juan Basin is as much as 20,000 feet (Kelley, 1957, p. 48).

The basin is bounded on the northeast by the broad Gallina-Archuleta Arch, a northwest-trending, asymmetric anticlinorium (fig. 2). This arch separates the much deeper San Juan Basin to the west from the shallower Chama Embayment to the east. Maximum structural relief between the arch and the San Juan Basin is about 13,000 feet, whereas the Chama Embayment is structurally only about 1,500 feet lower than the arch (Woodward and Callender, 1977, p. 211).

The eastern margin of the San Juan Basin is bounded by a prominent and structurally complex feature, the Nacimiento Uplift (fig. 2). In a classic geologic report, Woodward (1987) described the complex structural relations and geologic history of this area; the following summary is from that report.

The Nacimiento Uplift is a north-trending mountain block about 50 miles long and 6–10 miles wide and represents the southwestern limit of the Rocky Mountains. The northern part of the uplift terminates in a broad, north-plunging anticline that merges with the Gallina-Archuleta Arch, whereas the southern part terminates in south-plunging folds covered unconformably by Tertiary sedimentary rocks. In the most simplified model, the uplift generally consists of a block of Precambrian crystalline rocks that has been overthrust westward (fig. 4*B*). Structural relief between the highest part of the uplift and the San Juan Basin is at least 10,000 feet (Woodward, 1987, p. 49).

This report can only summarize the extremely complex structure of the western flank of the Nacimiento Uplift. In general, the western flank consists of northern and southern segments of two separate, major faults. The Nacimiento Fault (pl. 1) is a thrust fault extending northward from San Miguel Canyon. At great depths, the dip of this fault is steep to vertical (fig. 4*B*), but at shallow levels the dip flattens and becomes virtually horizontal (Woodward, 1987, p. 51, figs. 17–19). The maximum stratigraphic displacement along the Nacimientio Fault is about 4,000 feet; the maximum westward movement of the hanging wall is about 2,500 feet (Woodward, 1987, p. 52).

The Pajarito Fault (pl. 1) is a steep-angle reverse fault extending southward from San Miguel Canyon. The fault trace ranges in thickness from a knife edge to a 50-foot-wide zone of sheared Precambrian crystalline rocks. Maximum stratigraphic separation on the Pajarito Fault is about 3,600 feet (Woodward, 1987, p. 52). Craigg (1992) described the hydrogeology of saline springs associated with the discharge of deep ground water from the San Juan Basin along the Pajarito Fault.

Numerous other smaller faults (synthetic reverse faults, east-trending faults, antithetic reverse faults, and normal faults), en echelon folds, and other complex structures exist along the western face of the Nacimiento Uplift. A complexly faulted, steep, sometimes westward-dipping, sometimes overturned sinuous hogback of Paleozoic, Mesozoic, and Cenozoic rocks extends along the western face of the uplift; this hogback is the most complex part of the Hogback Monocline shown in figure 2. For detailed discussion and analysis of all aspects of the Nacimiento Uplift, the interested reader is referred to Woodward (1987).

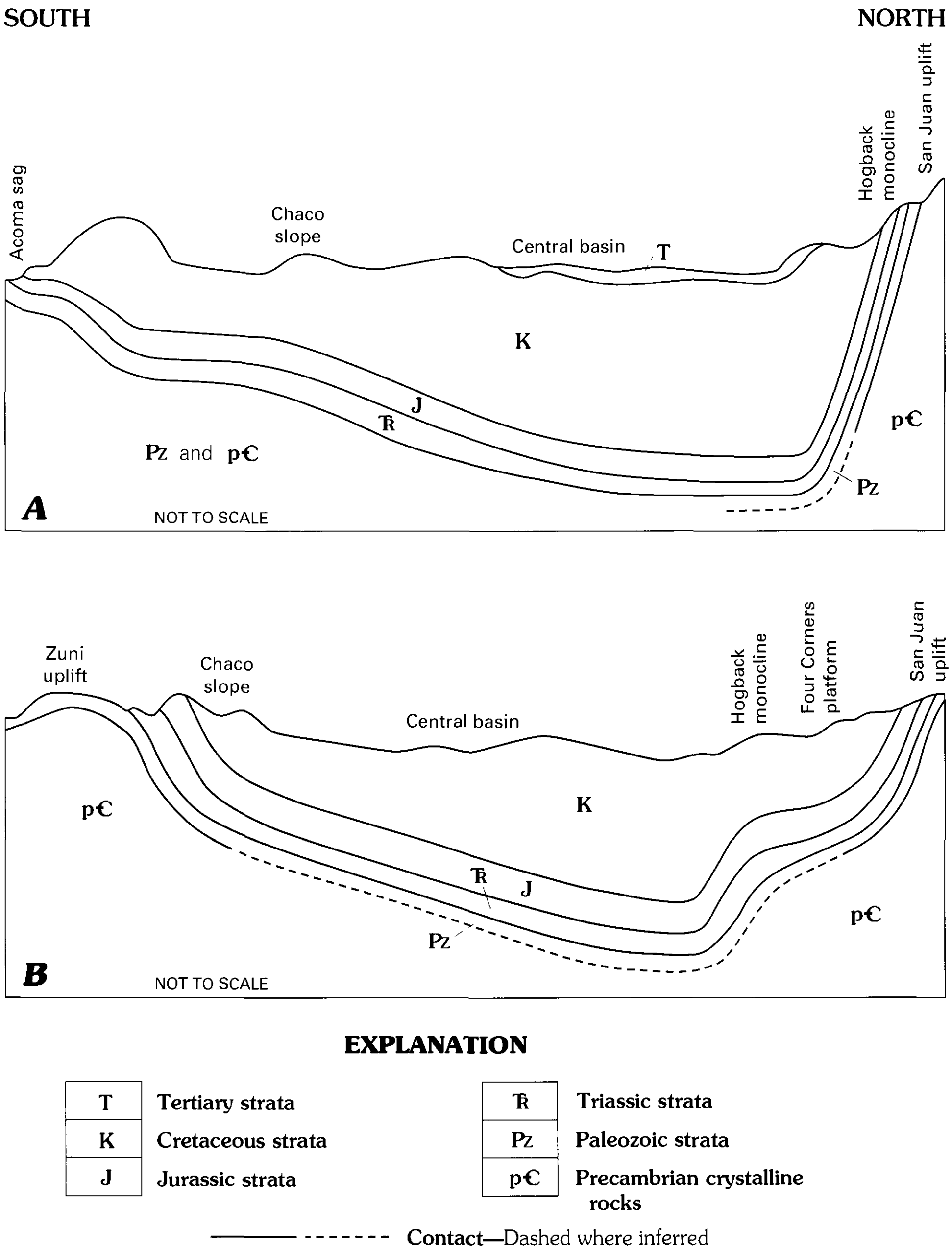
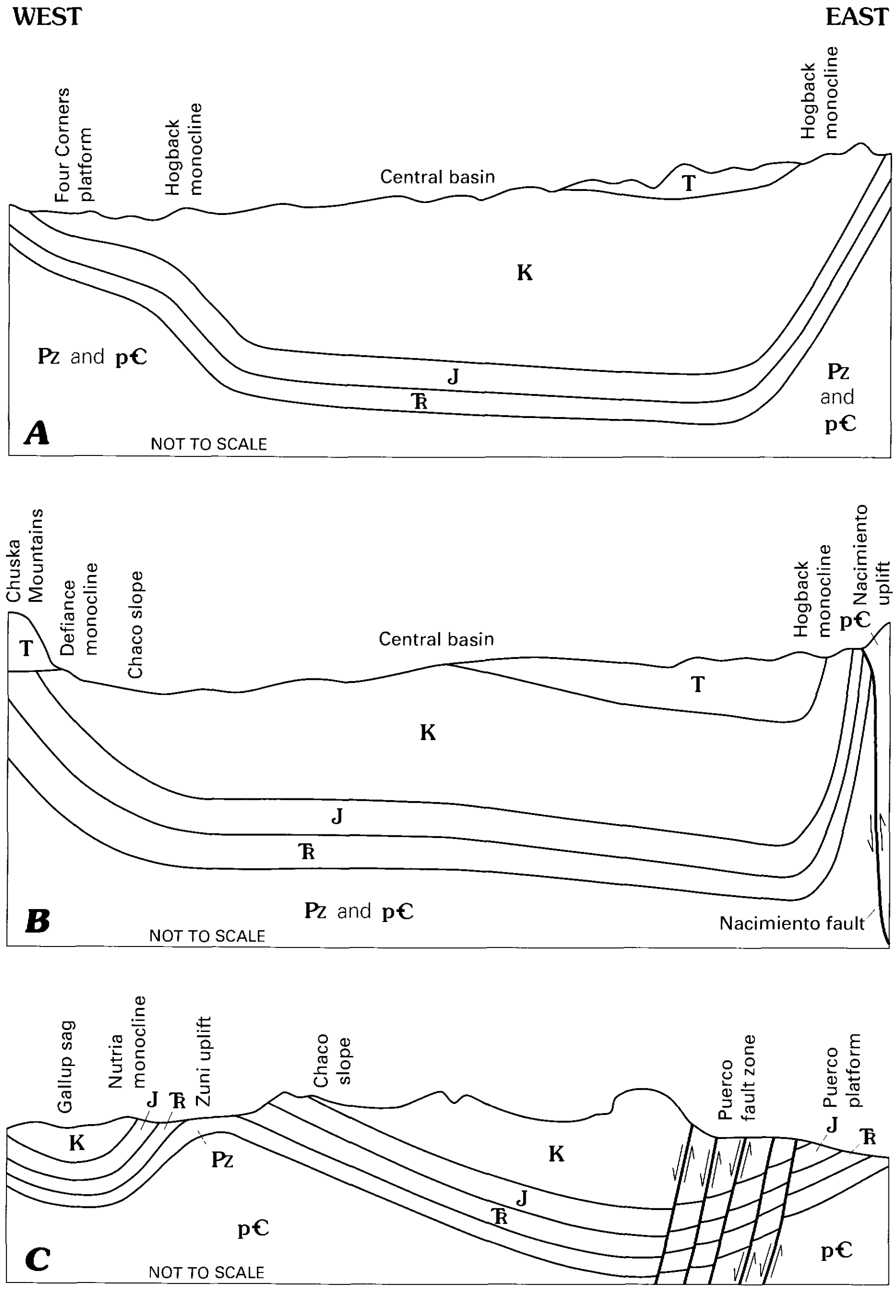


FIGURE 3.—Diagrammatic north-south-trending geologic sections showing principal structural features of the San Juan Basin. *A*, section from Acoma Sag through Chaco Slope, Central Basin, and Hogback Monocline to San Juan Uplift. *B*, section from Zuni Uplift through Chaco Slope, Central Basin, Hogback Monocline, and Four Corners Platform to San Juan Uplift.

The San Juan Basin is bounded on the southeast by three features: the extensively fractured Rio Grande Rift (a post-Laramide structure), the Ignacio Monocline, and the Lucero Uplift (fig. 2). The gradual structural rise of the southeastern part of the San Juan Basin terminates against the complexly faulted western margin of the Rio Grande Rift, a late Cenozoic extensional feature that is partly bounded on the west by the Ignacio Monocline. The Lucero Uplift is a northeast-trending structure about 30 miles long and 14 miles wide with a structural relief of about 2,500 feet (Kelley, 1950, p. 103). The broad, synclinal Acoma Sag is located between the Lucero Uplift on the east and the Zuni Uplift on the west (fig. 2).

The south-central margin of the San Juan Basin is bounded by the northwest-trending Zuni Uplift (figs. 2, 3*B*, and 4*C*). This domal feature consists of a Precambrian crystalline-rock core and prominent southwest- and north-east-facing dip slopes of upper Paleozoic sedimentary rocks.



EXPLANATION

T	Tertiary strata	TR	Triassic strata
K	Cretaceous strata	Pz	Paleozoic strata
J	Jurassic strata	p€	Precambrian crystalline rocks
———	Contact	⇌	Fault—Arrows show relative direction of movement

FIGURE 4.—Diagrammatic east-west-trending geologic sections showing principal structural features of the San Juan Basin. *A*, section from Four Corners Platform through Hogback Monocline (west limb) and Central Basin to Hogback Monocline (east limb). *B*, section from Chuska Mountains and Defiance Uplift through Chaco Slope and Central Basin to Hogback Monocline (east limb) and Nacimiento Uplift. *C*, section from Gallup Sag through Nutria Monocline, Zuni Uplift, Chaco Slope, and Puerco Fault Zone to Puerco Platform.

The southwestern limb of the uplift is known as the Nutria Monocline. The Zuni Uplift is about 80 miles long and as much as 35 miles wide. Structural relief between the highest part of the uplift and the San Juan Basin is as much as 5,500 feet (Kelley, 1950, p. 103).

In the southwest, the San Juan Basin is bounded by the northwestern part of the Zuni Uplift and the southern end of the north-trending Defiance Uplift (fig. 2). The steep eastern limb of the Defiance Uplift is known as the Defiance Monocline. A synclinal structural embayment, the Gallup Sag (fig. 2) is formed by the opposite-dipping limbs of the Nutria and Defiance Monoclines. The Zuni Embayment is a southern extension of the Gallup Sag.

Along the western margin, the San Juan Basin is bounded by the northern end of the north-trending Defiance Uplift. This prominent uplift forms the structural divide between the San Juan Basin to the east and the Black Mesa Basin to the west (fig. 2). The steeply dipping, sinuous Defiance Monocline (figs. 2, 4*B*) forms the eastern face of the uplift. The Defiance Uplift is about 100 miles long and 30 miles wide, with a maximum structural relief of about 8,000 feet (Kelley, 1957, p. 44) above the San Juan Basin.

In the northwest, prominent laccolithic masses of the Carrizo Mountains, Sleeping Ute Mountain, and La Plata Mountains bound the San Juan Basin (fig. 2). These laccoliths rise from the extensive, low structural feature known as the Four Corners Platform.

OTHER MAJOR STRUCTURAL ELEMENTS

The Puerco Platform and Puerco Fault Zone (figs. 2, 4*C*) mark the southeastern limit of the San Juan Basin and Colorado Plateau. Collectively, these northeast-trending features are about 35 miles long and 7–22 miles wide (Kelley, 1957, p. 47). To the north, the Puerco Platform merges with the Puerco Fault Zone and the Chaco Slope. To the east, the platform is bounded by the Ignacio Monocline and the Rio Grande Rift. To the south, the platform merges with the Acoma Sag, and to the west, it is bounded by Mount Taylor. The Puerco Fault Zone is characterized by northeast-trending, steep-angle normal faults (pl. 1), most of which are downthrown to the west (Kelley, 1957, p. 47; Craigg, 1980, p. 27). Most of the faults have maximum displacements ranging from only a few tens of feet to as much as 150 feet (Craigg, 1980, p. 27), but Kelley (1957, p. 47) reported between 1,000 and 2,000 feet of displacement on a few faults; however, he did not specify the location of these faults. Craigg (1980, p. 27) reported that the major geologic units typically are not completely offset along these faults. Also, the dip of the Mesozoic strata becomes steeper and the faults rise in a steplike manner toward the western flank of the Nacimiento Uplift (Craigg, 1980, p. 27). It is uncertain how deep the faulting in the Puerco Fault Zone actually extends into the subsurface. Also present on the Puerco Platform and within the Puerco Fault Zone are a series of northeast-trending basaltic dikes, exhumed volcanic necks, and Tertiary basalt flows (Craigg, 1980, p. 27–31).

The prominent Chaco Slope (fig. 2) is a somewhat arbitrarily defined structural element of the San Juan Basin (Kelley, 1957, p. 46). The slope is a broad, northwest-trending platform that is south of the Central Basin and north of the Puerco Platform, Puerco Fault Zone, and Zuni Uplift (fig. 2). The Chaco Slope is about 110 miles long and 30–40 miles wide. The regional dip of the rocks forming this platform is about 1° northward, and structural relief between the platform and the Central Basin is about 2,500 feet (Kelley, 1957, p. 46). Locally, the dip of the rocks forming the Chaco Slope is steeper, as it is along the northern part of the Zuni Uplift and also where the platform merges with the southern part of the Central Basin (figs. 3, 4*C*).

The Four Corners Platform (fig. 2) is a broad, prominent, northeast-trending structural element in the northwestern part of the San Juan Basin. The platform is distinctly bounded by the San Juan Uplift in the north, the Hogback Monocline in the east, and the Defiance Uplift in the southwest (figs. 2, 3*B*, and 4*B*). However, the platform boundary is difficult to delineate where it merges gradually with the Central Basin (southeast), Chaco Slope (south), and the Blanding and Paradox Basins of Utah and Colorado, which are to the northwest of the San Juan Basin (fig. 2). The dip of the rocks forming the platform steepens where it merges with the Central Basin along the Hogback Monocline (fig. 4*A*). The maximum structural relief between the Four Corners Platform and the Central Basin is about 4,000 feet (Kelley, 1957, p. 44).

The Hogback Monocline is a long, arcuate structural feature that extends northward from the Rio Grande Rift in the southeastern part of the San Juan Basin to the San Juan Uplift in the northern part of the basin and then southwestward for about 100 miles (fig. 2). Along the western flank of the Nacimiento Uplift, the rocks forming the Hogback Monocline are complexly faulted and locally overturned (Woodward, 1987, p. 55; Craigg, 1992). The Hogback Monocline forms all but the southern and southwestern boundaries of the Central Basin (fig. 2). The rocks forming the monocline dip steeply into the Central Basin (figs. 3, 4*A*, and 4*B*).

The Central Basin is a nearly circular (fig. 2) bowl-shaped depression that is deeper in the north and northeast. Along its southern margin, the Central Basin has a slightly dipping limb that merges with the Chaco Slope (figs. 3, 4*B*, and 4*C*). The axis of the San Juan Basin strikes eastward through the northern part of the Central Basin. The deepest part of the San Juan Basin is in the north-central part of the Central Basin, beneath the Navajo Reservoir (pl. 1) in New Mexico. The depth to Precambrian crystalline rocks in the deepest part of the basin is about 14,400 feet (Fassett and Hinds, 1971, p. 4).

GEOLOGIC UNITS

Professional Paper 1420 was approved for publication by the Director, U.S. Geological Survey, in 1992. The stratigraphic nomenclature used herein reflects the state of geologic knowledge circa 1990. Subsequent workers may have proposed minor changes in the nomenclature of certain geologic units in the interim between Director's approval and publication of this report.

No attempt is made herein to incorporate any stratigraphic nomenclature changes made since Director's approval, because the other major reports for the San Juan Basin RASA (Geochemistry—Dam, 1995; Ground-Water Modeling—Kernodle, 1996; and Summary—Levings and others, 1996) cite Professional Paper 1420 as in press and use many of the same illustrations including the stratigraphic diagrams, formation thickness maps, altitude of top of formation maps, and cite the geologic map. The ten Hydrologic Investigations Atlases (HA-720-A through J) published during this RASA also use the same stratigraphic nomenclature.

Superposed on the San Juan Basin is a thick sedimentary rock sequence mainly ranging from Devonian through Tertiary age, with the largest portion being Pennsylvanian through Tertiary (fig. 5). The maximum thickness of this sequence above the Precambrian crystalline-rock basement of the Central Basin is about 14,400 feet (Fassett and Hinds, 1971, p. 4). Basin structural history, as well as depositional history, is recorded in the unconformities and intertonguing of these rocks, in the faults that transect and monoclines that tilt the rocks, and in the igneous bodies that intrude the rocks. Evidence of the Laramide orogeny during latest Late Cretaceous and early Tertiary time is especially evident in the unconformities at the bases of lower Tertiary rocks (Condon and Huffman, 1989, p. 17, 18).

The sedimentary rock sequence of the San Juan Basin dips inward from the basin margins toward the trough-like structural center, or deepest part of the Central Basin (fig. 6; pl. 1). Older sedimentary rocks crop out around the basin margins and are successively overlain by younger strata toward the basin center, much like a set of nested bowls.

The San Juan Basin RASA study area, as defined earlier, is that part of the San Juan Basin that contains rocks of Triassic through Tertiary age. These rocks are emphasized because they contain the principal aquifers and confining units in the basin. The general geologic characteristics of the rocks are summarized in table 1. Although not discussed in this report, volcanic rocks of Tertiary and Quaternary age and various unconsolidated surficial deposits (alluvial, eolian, landslide, talus, and terrace deposits) also are present in the basin (pl. 1).

TRIASSIC ROCKS

Sedimentary rocks of Triassic age in the San Juan Basin consist of the Moenkopi Formation, Moenkopi(?) Formation, Chinle Formation, and Dolores Formation. The Moenkopi Formation is of Early and Middle Triassic age, and the Chinle and Dolores Formations are of Late Triassic age. Triassic rocks crop out along the basin boundaries (pl. 1) and are present in the subsurface throughout the basin. Regionally, Triassic rocks disconformably overlie Permian rocks throughout most of the San Juan Basin (fig. 5); in the eastern and northern parts of the basin, however, Triassic rocks disconformably overlie Pennsylvanian or Precambrian rocks (O'Sullivan, 1977, p. 139). In most of the basin, Triassic rocks are disconformably overlain by the Entrada Sandstone of Middle Jurassic age.

Triassic rocks generally consist of deposits from various nonmarine (stream channel, flood plain, eolian, and lacustrine) environments. In the San Juan Basin, the maximum total thickness of Triassic strata is about 1,650 feet; the thickness increases toward the southwest, from zero near Pagosa Springs, Colo., to a maximum of about 1,650 feet along the New Mexico-Arizona State line (fig. 7) (O'Sullivan, 1977, p. 140). The general lithologies and maximum thicknesses of Triassic rocks are summarized in table 1.

MOENKOPI AND MOENKOPI(?) FORMATIONS

The Moenkopi Formation was named by Ward (1901) for exposures along the mouth of Moenkopi Wash at the junction with the Little Colorado River in Coconino County, Ariz. In the San Juan Basin, the Moenkopi is present only along an isolated strip west of the New Mexico-Arizona State line in the Defiance Uplift. In this area, the Moenkopi consists solely of the Holbrook Member (Stewart and others, 1972b, p. 26), which generally consists of reddish-brown mudstone and siltstone with lesser amounts of fine-grained sandstone. The maximum thickness is about 50 feet (O'Sullivan, 1977, p. 139).

Although throughout most of its extent the Moenkopi Formation was deposited on a broad shelf along the margins of a transgressing sea, in the San Juan Basin it mainly was deposited in fluvial environments (O'Sullivan, 1977, p. 145). The Moenkopi disconformably overlies sedimentary rocks of Permian age and is disconformably overlain by the Shinarump Member of the Chinle Formation of Late Triassic age.

Along the southern margin of the San Juan Basin, in the Zuni Mountains-Fort Wingate-Bluewater Lake area, outcropping strata tentatively have been correlated with the Moenkopi Formation. These deposits have been referred to as the Moenkopi(?) Formation by some geologists (Stewart and others, 1972b, p. 26; O'Sullivan, 1977, p. 139). A 30-mile

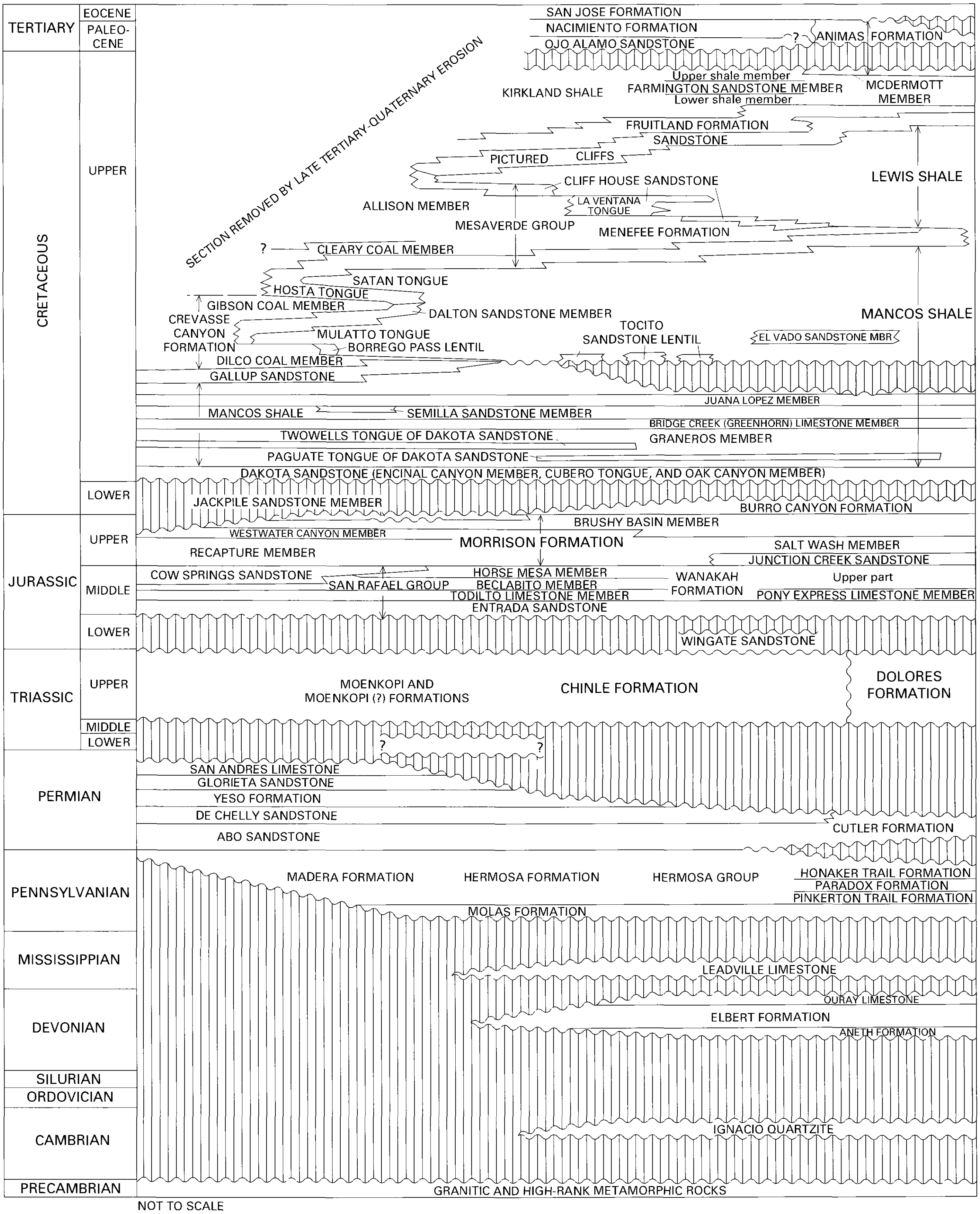


FIGURE 5.—Stratigraphic framework and nomenclature of the San Juan Basin in a general north-south direction. Modified from Molenaar (1977a, b; 1989).

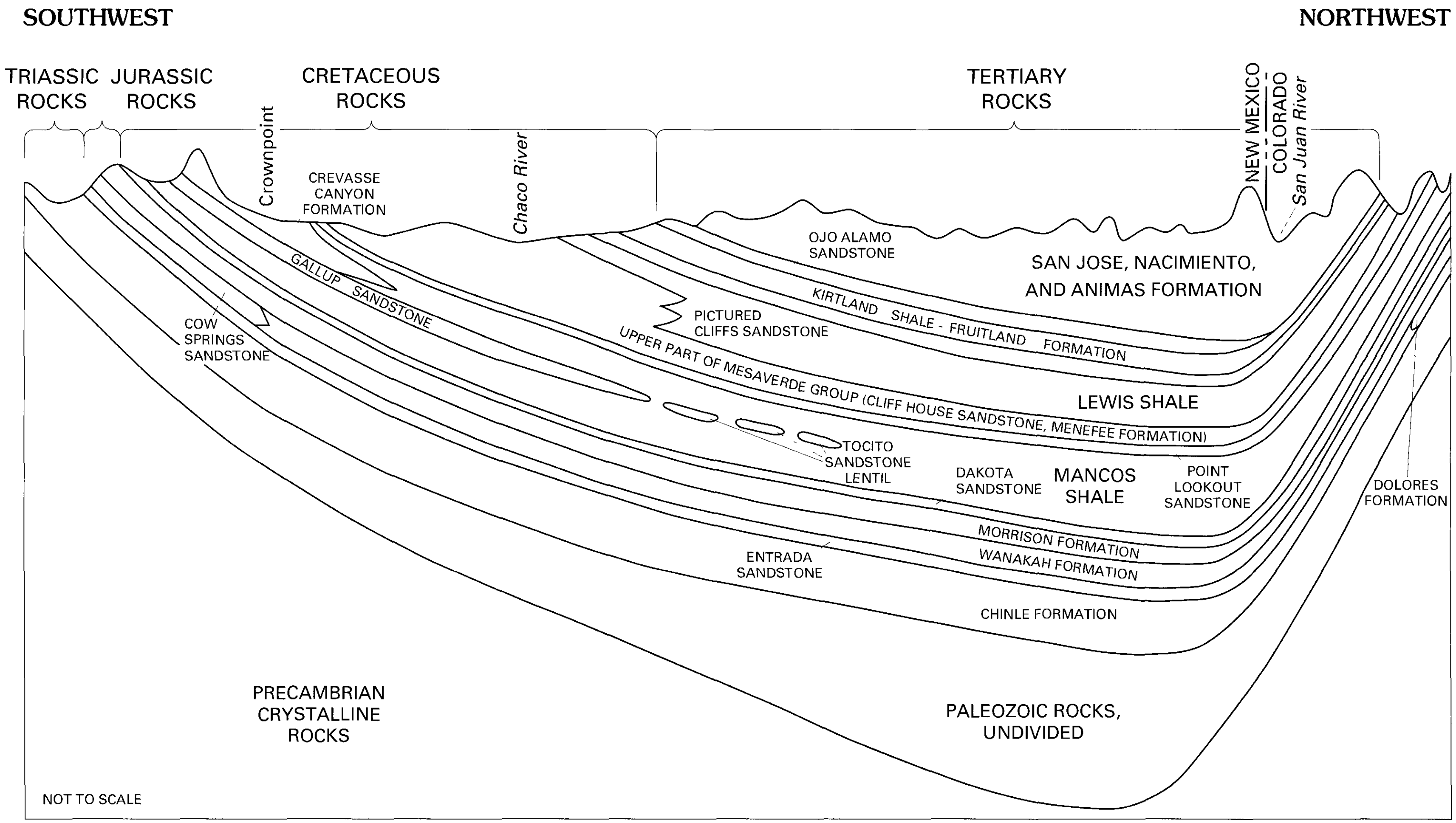
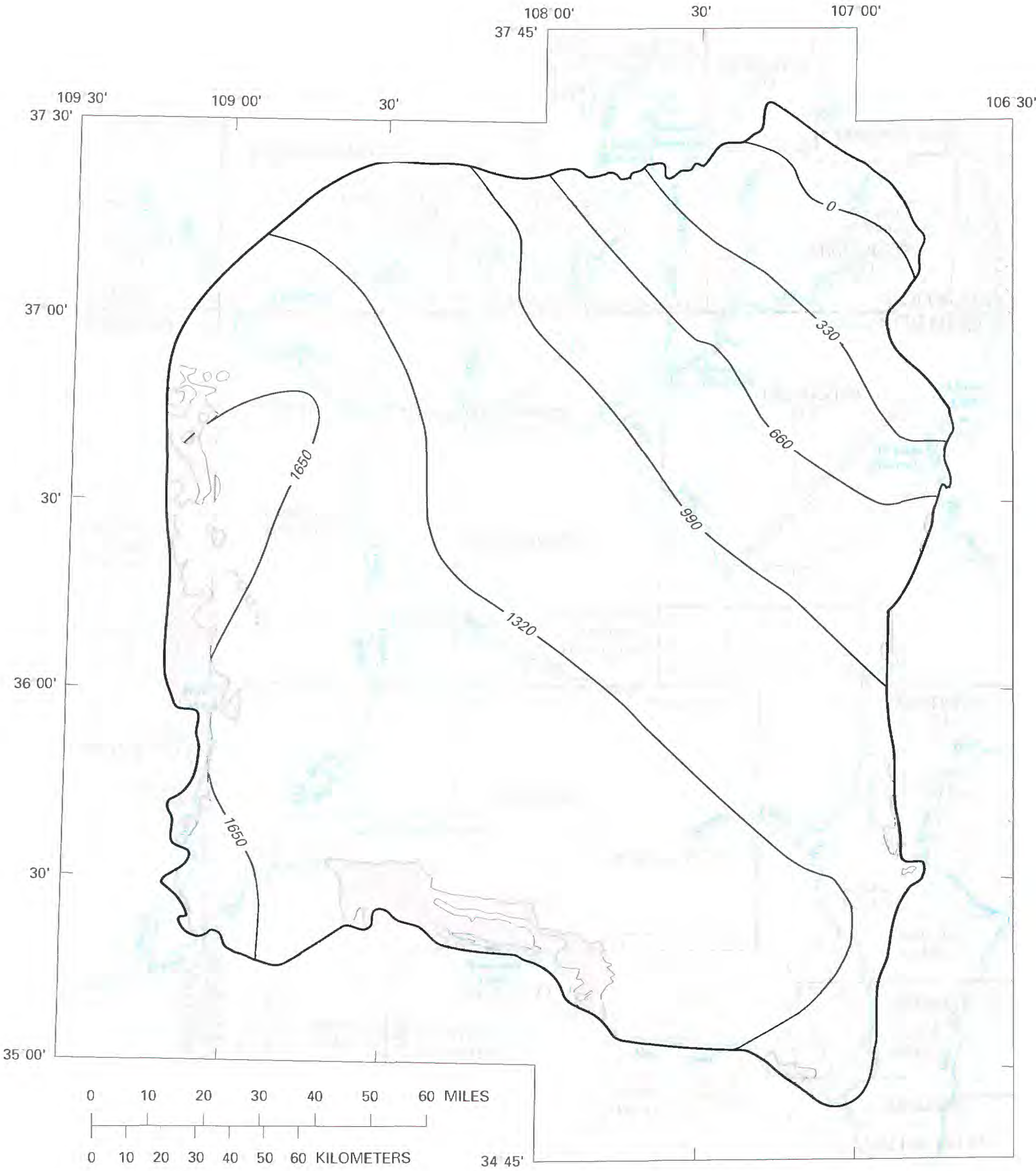


FIGURE 6.—Diagrammatic northeast-trending stratigraphic section through the San Juan Basin showing the trough-like structure. Modified from Lyford (1979, fig. 3).



EXPLANATION

Outcrops of Triassic rocks—From Dane and Bachman (1965), Wilson and others (1969), and Tweto (1979)

Boundary of study area

— *1650* — **Structure contour**—Shows approximate thickness of Triassic rocks. Interval 330 feet

FIGURE 7.—Approximate thickness of undivided Triassic rocks in the San Juan Basin study area. Modified from O'Sullivan (1977, fig. 1). Contour interval is 330 feet.

TABLE 1.—*Summary of geologic characteristics for Triassic through Tertiary formations in the San Juan Basin Regional Aquifer-System Analysis study area*

[Formations are listed in stratigraphic order with the youngest at the top. Figures 3–6 and 8 show stratigraphic relations of these formations]

System	Formation	Approximate maximum depth to top (feet)	Approximate maximum thickness (feet)	General lithologic description
Tertiary.........	Chuska Sandstone	At surface in western part of basin	1,750	Massive, crossbedded, very fine to coarse-grained sandstone; minor interbeds of siltstone and shale; eolian
	San Jose Formation	At surface inside the Central Basin	2,700	Interbedded very fine to coarse-grained, locally conglomeratic arkosic sandstone and siltstone and variegated shale; fluvial
	Nacimiento Formation	[1] 2,600	1,300	Interbedded gray shale and discontinuous lenses of arkosic sandstone; locally constant carbonaceous lenses; lacustrine and fluvial
	Animas Formation (includes McDermott Member)	[1] 2,600	2,700	Interbedded tuffaceous sandstone, conglomerate, and shale; McDermott Member distinctly purple; fluvial
	Ojo Alamo Sandstone	3,500	400	Overlapping sheetlike sequences of arkosic sandstone and conglomerate; locally contains interbedded lenses of shale; fluvial
Cretaceous.....	Kirtland Shale and Fruitland Formation (combined)	3,500	2,000	Interbedded repetitive sequences of lenticular sandstone, siltstone, shale, and claystone; carbonaceous shale and coal common in Fruitland; fluvial and "coal" swamp environments
	Pictured Cliffs Sandstone	4,000	400	Upward-coarsening, very fine to medium grained sandstone with thin interbeds of dark shale in lower part; regressive marine
	Lewis Shale	4,000–4,500	2,400	Dark shale and silty shale with thin interbeds of silty limestone, siltstone, and fine-grained sandstone in lower part; intertongues with Pictured Cliffs and Cliff House Sandstones; offshore marine
	Cliff House Sandstone	6,000	Individual tongues discussed in text	Several very fine to fine-grained sandstone tongues; common interbeds of dark shale; transgressive marine
	Menefee Formation	6,000–6,500	2,000	Interbedded sequences of lenticular sandstone, siltstone, dark shale, and claystone; carbonaceous shale and coal common in lower and upper parts; fluvial and "coal" swamp environments
	Point Lookout Sandstone	6,000–6,500	415	Very fine to medium-grained sandstone with thin interbeds of dark shale in lower part; regressive marine
	Crevasse Canyon Formation	[1] 3,200	750	Interbedded sequences of lenticular sandstone, siltstone, shale, and claystone with carbonaceous shale and coal common in lower and upper parts; fluvial and "coal" swamp environments. Also contains regressive marine deposits; Dalton Sandstone Member is in middle part (members discussed in text)
	Gallup Sandstone	4,500	300	Sandstone with some conglomerate, shale, carbonaceous shale, and coal; mainly regressive marine but also contains deposits of continental environments
	Mancos Shale	7,000	2,300	Dark shale and silty shale with thin interbeds of silty limestone, siltstone, and fine-grained sandstone; intertongues with Point Lookout, Gallup, and Dakota Sandstones; offshore marine
	Dakota Sandstone	8,500	500	Several members and tongues of fine- to coarse-grained sandstone with dark shale, siltstone, and minor carbonaceous shale; mainly transgressive marine, but lower

TABLE 1.—*Summary of geologic characteristics for Triassic through Tertiary formations in the San Juan Basin Regional Aquifer-System Analysis study area*—Continued.

[Formations are listed in stratigraphic order with the youngest at the top. Figures 3–6 and 8 show stratigraphic relations of these formations]

System	Formation	Approximate maximum depth to top (feet)	Approximate maximum thickness (feet)	General lithologic description
				part contains fluvial deposits
	Burro Canyon Formation	Not known	200	Fine- to coarse-grained sandstone and conglomeratic sandstone interbedded locally with shale; fluvial
Jurassic..........	Morrison Formation	8,500	1,100	Fine- to coarse-grained locally conglomeratic sandstone, sandy siltstone, shale, and claystone; also contains thin limestone beds; various continental environments (members discussed in text)
	Junction Creek Sandstone	Not known	500	Crossbedded fine- to coarse-grained quartzose sandstone with arkosic sandstone and shale lenses; mostly eolian
	Cow Springs Sandstone	Not known	300	Crossbedded fine- to medium-grained quartzose and arkosic sandstone; eolian
	Wanakah Formation	9,500	[2]200	Limestone, gypsum, claystone, very fine to fine-grained silty sandstone, and coarse-grained sandstone; lacustrine, eolian, and fluvial (members discussed in text)
	Entrada Sandstone	[1]9,300	330	Crossbedded silty sandstone and very fine to medium-grained quartzose sandstone; eolian
	Wingate Sandstone	Not known	Not known	Crossbedded very fine to medium-grained sandstone; eolian
Triassic..........	Dolores Formation	Not known	1,200(?)	Siltstone and very fine to fine-grained sandstone with limestone conglomerate lenses; fluvial
	Chinle Formation	[1]9,700	1,650	Variegated claystone and shale, siltstone, sandstone, conglomerate, and limestone; various continental environments (members discussed in text)
	Moenkopi Formation	Not known	50	Variegated mudstone and siltstone with lesser amounts of fine-grained sandstone; fluvial
	Moenkopi(?) Formation	Not known	150	Variegated mudstone and siltstone, sandstone, and quartz-pebble conglomerate; fluvial

[1]Stone and others, 1983.
[2]Molenaar, 1989.

gap exists between outcrops of the Moenkopi(?) and their probable equivalents in the Defiance Uplift area to the northwest (Stewart and others, 1972b, p. 28).

The Moenkopi(?) Formation disconformably overlies the San Andres Limestone of Permian age and is disconformably overlain by the Shinarump Member of the Chinle Formation. The Moenkopi(?) was deposited by streams draining into the Triassic sea in Arizona (O'Sullivan, 1977, p. 145). Lithologically, the Moenkopi(?) generally consists of variegated sequences of slope-forming mudstone and siltstone, ledge-forming sandstone, and quartz-chert pebble conglomerate (Stewart and others, 1972b, p. 26–28).

The thickness of the Moenkopi(?) Formation ranges from about 50 feet in the Zuni Mountains to about 150 feet in the Bluewater Lake area. Outcrops of the Moenkopi(?) might not be present at all Triassic-rock localities in this area, and the eastward extent of the formation is uncertain (Stewart and others, 1972b, p. 27). The geologic characteristics (fine-grained lithologies, isolated lenses, and limited areal extent) of the Moenkopi and Moenkopi(?) Formationsmake them unimportant as aquifers in the San Juan Basin.

CHINLE FORMATION

Gregory (1917, p. 42–48) defined the Chinle Formation for characteristic exposures in Chinle Valley west of Canyon de Chelly, Apache County, Ariz. The Chinle crops out along the western flank of the Sierra Nacimiento, along Interstate 40 between Grants and Gallup, N. Mex., and in the western part of the Defiance Uplift along the New Mexico and Arizona State line (pl. 1). The Chinle is present in the subsur-

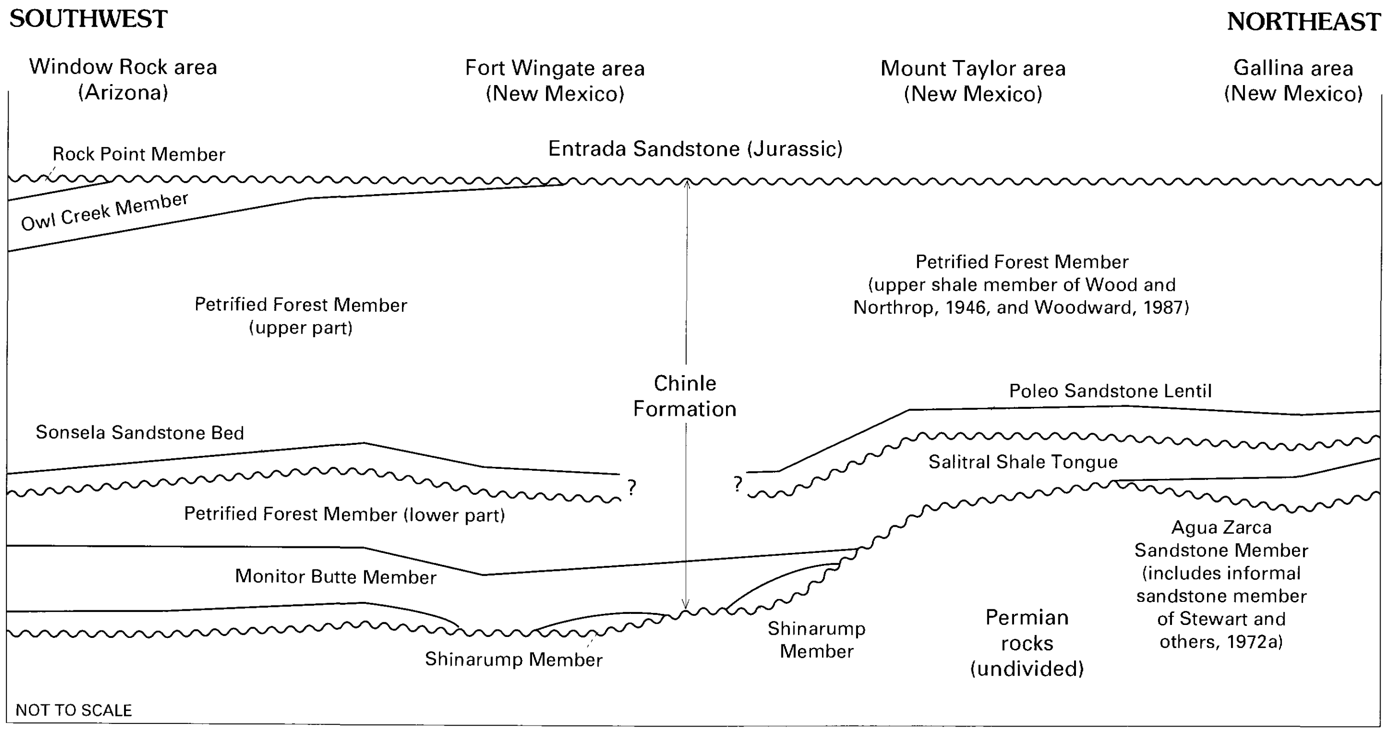


FIGURE 8.—Diagrammatic subsurface stratigraphic correlation of units in the Chinle Formation. Modified from Stewart and others (1972a, fig. 8) and O'Sullivan (1974, fig. 2).

face throughout the San Juan Basin; its equivalent, the Dolores Formation (fig. 5), is present in the subsurface and crops out in southwestern Colorado (pl. 1). Regionally, the Chinle disconformably overlies rocks of Permian age (figs. 5, 8). The Chinle typically forms broad valleys (especially along Interstate 40 between Grants and Gallup, beneath the red cliffs of the Entrada Sandstone); locally, erosion-resistant sandstone or conglomerate layers cap small buttes or form rough ledges, cliffs, or dip slopes.

In general, the Chinle Formation consists of strata deposited in various continental (stream channel, flood plain, lake, swamp, and dune) environments. The formation contains variegated claystone, shale, siltstone, sandstone, conglomerate, and limestone beds of varying thickness. The Chinle has been subdivided into several members. The following descriptions mainly are taken from Wood and Northrop (1946), Repenning and others (1969), Stewart and others (1972a), O'Sullivan (1977), Woodward (1987), and Dubiel (1989a, b).

In the southern, western, and northwestern parts of the San Juan Basin, the Chinle Formation includes (in ascending order) the Shinarump, Monitor Butte, Petrified Forest (and Sonsela Sandstone Bed), Owl Rock, and Rock Point Members (fig. 8). The Shinarump Member mostly is lenticular, crossbedded, coarse-grained, conglomeratic sandstone. Color varies from yellowish orange, grayish purple, and yellowish gray to brown; locally the sandstone is mottled. Minor pale-red to greenish-gray mudstone lenses also are present. The contact with underlying Permian rocks is a deeply scoured erosion surface. In the San Juan Basin, the Shinarump Member is present as isolated lenses of local extent with a maximum thickness of about 25 feet near Fort Wingate (O'Sullivan, 1977, p. 139).

The Monitor Butte Member mainly consists of interbedded red mudstone, gray to red siltstone, sandstone, and conglomerate. It locally intertongues with the underlying Shinarump and overlying Petrified Forest Members (Repenning and others, 1969, p. 20). The thickness of the Monitor Butte decreases from about 300 feet in the Canyon de Chelly area of Arizona until it pinches out near Mount Taylor in New Mexico (fig. 8) (O'Sullivan, 1974, fig. 2; and 1977, p. 141).

The Petrified Forest Member is the most widespread member of the Chinle Formation throughout the Colorado Plateau and the San Juan Basin (fig. 8) (Repenning and others, 1969, p. 21; O'Sullivan, 1974, fig. 2, p. 172, 173). It mainly consists of variegated gray, brown, red, and purple mudstone, shale, and siltstone. In the southern and western parts of the basin, it is divided into a lower and upper part by the Sonsela Sandstone Bed (fig. 8). The lower part thins from about 300 feet in the Canyon de Chelly area to about 100 feet in the eastern part of the Zuni Uplift (O'Sullivan, 1977, p. 141). The upper part thickens from about 400 feet in the Canyon de Chelly area, to about 850 feet near Fort Wingate, to about 1,100 feet near Thoreau, N. Mex. (Repenning and others, 1969, p. 23). Several isolated sandstone lenses as much as 40 feet thick are present in the upper part of the Petrified Forest Member (O'Sullivan, 1977, p. 141). The Sonsela Sandstone Bed is a gray to yellowish-gray, crossbedded, conglomeratic sandstone unit with interbedded siltstone and shale. This bed is widespread in the southwestern part of the basin and averages about 50 feet thick; near Grants, it is as much as 300 feet thick (O'Sullivan, 1977, p. 141). Cooley (1959, p. 71), Strobell (1964, p. 100), and O'Sullivan (1974, fig. 2, p. 172–173) suggested that the Sonsela Sandstone Bed and the Poleo Sandstone Lentil of the Chinle Formation in the eastern San Juan Basin might be correlative units.

The Owl Rock Member of the Chinle Formation mainly consists of mottled pink to red, calcareous silty shale interbedded with erosion-resistant, ledge-forming cherty limestone and calcareous siltstone and sandstone. This member forms a conspicuous ledge below the Entrada Sandstone cliffs north of Interstate 40 between Gallup and Thoreau. In the Canyon de Chelly area, the Owl Rock Member is about 300 feet thick but thins eastward until it disappears near Thoreau because of erosion prior to deposition of the Entrada Sandstone (fig. 8) (O'Sullivan, 1974, fig. 2).

Recent revisions in the nomenclature of the Chinle Formation and the Jurassic Wingate Sandstone have resulted in removing the Rock Point Member from the Wingate and placing it in the upper part of the Chinle. Dubiel (1989b, p. 213) has shown that the Rock Point Member is stratigraphically equivalent to the Church Rock Member of the Chinle Formation in the Monument Valley area of northeastern Arizona and also the upper member of the Dolores Formation in southwestern Colorado. The Rock Point Member is present in the Defiance Uplift-Gallup Sag-Zuni Embayment areas and generally consists of alternating beds of horizontally laminated or crossbedded, variegated siltstone, silty sandstone, or very fine grained sandstone (Stewart and others, 1972a, p. 44). This part of the Rock Point Member probably was deposited in alternating lacustrine and eolian environments (Stewart and others, 1972a, p. 99; Dubiel, 1989b, p. 219). In the southern part of the depositional area, the member locally contains conglomerate and conglomeratic sandstone beds of fluvial origin that have informally been termed "the beds at Lupton" by O'Sullivan and Green (1973, p. 77). The maximum thickness of the Rock Point Member is about 500 feet in the northern part of the Defiance Uplift, but it thins in all directions from that area (Stewart and others, 1972a, fig. 24; Cooley and Weist, 1979, p. 60).

In the north-central and eastern parts of the San Juan Basin, the Chinle Formation consists of (in ascending order) the Agua Zarca Sandstone Member, Salitral Shale Tongue, Poleo Sandstone Lentil, and Petrified Forest Member (fig. 8) (Stewart and others, 1972a; O'Sullivan, 1974, 1977; Woodward, 1987; and Dubiel, 1989a). The Agua Zarca Sandstone Member was named by Wood and Northrop (1946) for exposures southeast of the village of Gallina in Rio Arriba County, N. Mex. This member is a cliff-forming fluvial unit that disconformably overlies Permian rocks and has gradational contacts with the overlying Salitral Shale Tongue and locally with the overlying Petrified Forest Member (Woodward, 1987, p. 31). The Agua Zarca Sandstone Member typically consists of white to light-gray and red to purple, very fine to coarse-grained, crossbedded, locally conglomeratic sandstone. Wood and Northrop (1946) and Woodward (1987, p. 31) recognized the Agua Zarca Sandstone Member from the San Pedro Mountain area southward to the area around San Ysidro, N. Mex. Stewart and others (1972a, p. 21–24) and O'Sullivan (1974, p. 171), however, did not recognize the Agua Zarca Sandstone Member as far south as San Ysidro and instead designated an informal member they called the "sandstone member." In this report, the terminology of Wood and Northrop (1946) and Woodward (1987, p. 31) is used because the two members intertongue, have the same general lithology, and occupy the same stratigraphic position. The thickness of the Agua Zarca Sandstone Member is variable but generally thins northward from as much as 250 feet near San Ysidro until it disappears north of San Pedro Mountain, near Gallina, (Woodward and Ruetschilling, 1976; Woodward, 1987, p. 1).

The Salitral Shale Tongue also was named by Wood and Northrop (1946) for exposures between the villages of Gallina and Coyote in Rio Arriba County, N. Mex. The Salitral Shale Tongue conformably overlies the Agua Zarca Sandstone Member and disconformably overlies Permian rocks in the Mount Taylor area. It is disconformably overlain by the Poleo Sandstone Lentil (fig. 8). The Salitral Shale Tongue was deposited in a lacustrine environment and consists mainly of red, maroon, brown, and greenish-gray shale with ubiquitous calcareous nodules. Lenticular, very fine to coarse-grained sandstone beds locally also are present. The Salitral Shale Tongue is lithologically similar to the Petrified Forest Member and cannot be recognized as a separate unit where the overlying Poleo Sandstone Lentil is absent (O'Sullivan, 1974, p. 172; Woodward, 1987, p. 1). The thickness of the Salitral Shale Tongue is variable but generally decreases toward the north and east from a maximum of about 300 feet just northeast of La Ventana, N. Mex., to about 110 feet in the northern part of the Sierra Nacimiento, to zero near Gallina (O'Sullivan, 1974, p. 171; Woodward, 1987, p. 31).

The term "Poleo" was first used in a geologic sense by Huene (1911), who named exposures just southwest of Coyote the "Poleo top sandstone." Wood and Northrop (1946) redefined the unit as a lentil in the Chinle Formation. The Poleo Sandstone Lentil disconformably overlies the Salitral Shale Tongue, and its upper contact is conformable and gradational with the Petrified Forest Member (fig. 8) (Stewart and others, 1972a, p. 35; O'Sullivan, 1974, fig. 2). The Poleo Sandstone Lentil is present in the northern part of the Sierra Nacimiento and in the San Pedro Mountain area, where it attains its maximum thickness of about 130 feet; the lentil pinches out southward near San Miguel Canyon, northeast of La Ventana (Woodward, 1987, p. 31). The Poleo Sandstone Lentil is a high-energy fluvial deposit mostly consisting of ridge- and cliff-forming, yellowish-gray to greenish, very fine to coarse-grained, crossbedded sandstone. The sandstone locally is conglomeratic with pebbles of chert, quartz, quartzite, and limestone.

The Petrified Forest Member in the north-central and eastern San Juan Basin is about 1,100 feet thick in the southern part of the Sierra Nacimiento and thins northward to about 800 feet north of San Pedro Mountain near Gallina (Stewart and others, 1972a, p. 36, fig. 8; Woodward, 1987, p. 34). Wood and Northrop (1946) and Woodward (1987, p. 33, fig. 10) used the informal terminology "upper shale member" for that part of the Chinle above the Poleo Sandstone Lentil. Stewart and others (1972a, fig. 8), however, correlated the same part of the Chinle Formation with the Petrified Forest Member of the southern and western parts of the basin; their terminology is followed in this report.

In the Chinle Formation, water-yielding units mainly consist of local, lenticular sandstone bodies such as the Shinarump and Agua Zarca Sandstone Members (Cooley and Weist, 1979, p. 61–62; Stone and others, 1983, p. 41; Craigg, 1992). The Poleo Sandstone Lentil and Sonsela Sandstone Bed also have potential as minor aquifers.

DOLORES FORMATION

The Dolores Formation was defined by Cross and others (1899) from exposures in the Dolores River valley in southwestern Colorado. The term Dolores Formation, as presently used, generally is applied to rocks that are equivalent to parts of the Chinle Formation (fig. 5) (Stewart and others, 1972a, pl. 2). The Dolores was deposited in fluvial environments (O'Sullivan, 1977, p. 145) and disconformably overlies the Cutler Formation of Permian age. The Dolores is disconformably overlain by the Entrada Sandstone of Middle Jurassic age (fig. 5) (Stewart and others, 1972a, fig. 15).

The Dolores Formation is presently defined only in Colorado (pl. 1), and within the study area has been subdivided into informal lower, middle, and upper members by Stewart and others (1972a, p. 33) and O'Sullivan (1977, p. 143). These authors considered the lower and middle members to be equivalent to the Petrified Forest and Owl Rock Members of the Chinle Formation, and the upper member equivalent to what they considered the Rock Point Member of the Wingate Sandstone. These stratigraphic relations were discussed and shown graphically by Stewart and others (1972a, p. 34, 48–49, pl. 2). As was discussed in the preceding section, the Rock Point Member was subsequently removed from the Wingate Sandstone and placed in the upper part of the Chinle Formation (Dubiel, 1989b, p. 214).

The lower member of the Dolores Formation consists of ledge-forming, greenish-gray to yellowish-green, very fine to fine-grained, crossbedded sandstone with some limestone conglomerate. The thickness of the lower member ranges from about 20 feet along the Piedra River west of Pagosa Springs, Colo., to about 160 feet in the subsurface southwest of the outcrops near Durango, Colo. (Stewart and others, 1972a, p. 34, pl. 2).

The middle member of the Dolores Formation is a slope-forming, variegated red-bed unit consisting of siltstone, silty sandstone, and very fine grained sandstone. Thin, lenticular limestone conglomerate beds also are present. The thickness of the middle member ranges from about 130 feet along the Piedra River to about 270 feet along the Animas River north of Durango (Stewart and others, 1972a, p. 48).

The upper member of the Dolores Formation forms steep slopes. It also is a red-bed unit consisting of light-brown to reddish-brown siltstone and sandy siltstone containing isolated lenses of limestone conglomerate, but there are fewer such lenses in this member than in the middle member. The thickness of the upper member ranges from about 260 feet along the Animas River north of Durango to about 700 feet in the subsurface west of the Animas River. The upper member is absent in the Piedra River area (Stewart and others, 1972a, p. 48, 49).

JURASSIC ROCKS

Jurassic sedimentary rocks in the San Juan Basin consist of the Wingate Sandstone, Entrada Sandstone, Wanakah Formation, Cow Springs Sandstone, Morrison Formation, and Junction Creek Sandstone. The Wingate is of Early Jurassic age, and the Entrada, Wanakah, and Cow Springs are of Middle Jurassic age. The majority of the Junction Creek is of Late Jurassic age, but the lower part is Middle Jurassic (Condon and Huffman, 1988, p. 10). The Morrison Formation is of Late Jurassic age.

Jurassic rocks consist of strata deposited in various nonmarine environments (stream channel, flood plain, lake, dune, sabkha). The strata collectively attain a maximum thickness of about 1,500 feet in the west-northwestern part of the basin. The erosion surface at the base of the Upper Cretaceous Dakota Sandstone progressively truncates the Upper Jurassic strata toward the south until just south of the Zuni Uplift, where the entire Jurassic sequence has been removed and the Dakota disconformably overlies Upper Triassic rocks (Green and Pierson, 1977, p. 147). The general lithologies and thicknesses of Jurassic rocks are summarized in table 1; outcrops of these rocks are shown on plate 1.

WINGATE SANDSTONE

The Wingate Sandstone (of the Glen Canyon Group) originally was named by Dutton (1885) for the red cliff-forming unit north of Fort Wingate, N. Mex., but the formation has had a confusing history of nomenclature problems. Dutton's (1885) definition included all strata between the present Owl Rock Member of the Upper Triassic Chinle Formation and the Todilto Limestone Member of the Middle Jurassic Wanakah Formation. The cliff-forming part of the stratotype eventually was correlated with the Middle Jurassic Entrada Sandstone of southeastern Utah (Baker and others, 1947). West of the stratotype, only the lowermost deposits between the Owl Rock Member and the base of the Entrada were considered to be Wingate (Harshbarger and others, 1957, p. 8; Green and Pierson, 1977, p. 149). Nomenclature problems continue to develop because recent work by Green (1974) and Dubiel (1989b) has left the Wingate without a stratotype.

As currently defined, the Wingate Sandstone is recognized only along the extreme northwestern margins of the San Juan Basin (Green, 1974, p. 1; Green and Pierson, 1977, p. 149; Dubiel, 1989b, p. 213). It is found only west of a northeast-trending line that approximately connects Fort Defiance, Ariz., Shiprock, N. Mex., and Cortez, Colo. (O'Sullivan and Green, 1973, fig. 3–D). Where present, the Wingate unconformably overlies the Chinle Formation (Cooley and Weist, 1979, p. 60) and is unconformably overlain by the Entrada Sandstone (Green and Pierson, 1977, p. 150) (fig. 5).

The Wingate Sandstone formerly consisted of a lower unit, the Rock Point Member, and an upper unit, the Lukachukai Member (Harshbarger and others, 1957, p. 8). Green (1974), however, correlated rocks of the Lukachukai Member at the Fort Wingate section with the overlying Entrada Sandstone and renamed them the Iyanbito Member of the Entrada Sandstone. In the most recent nomenclature revision, Dubiel (1989b) has placed the Rock Point Member in the upper part of the Chinle Formation. Although the Wingate still exists as a sedimentary rock body, the work of Green (1974) has left the Wingate without a stratotype; Dubiel (1989b) formally abandoned the name Lukachukai Member because it was the only remaining member of the Wingate.

The Wingate Sandstone was deposited in an eolian environment and consists of homogeneous, light- to reddish-brown to orange, very fine to medium-grained sandstone. High-angle, large-scale crossbedding and massive vertical cliffs are characteristic features (Harshbarger and others, 1957, p. 11; O'Sullivan and Green, 1973, p. 76). The limited extent of the Wingate in the San Juan Basin makes it unimportant as a regional water-yielding unit.

ENTRADA SANDSTONE

The Entrada Sandstone was first described by Gilluly and Reeside (1928, p. 76) for outcrops at Entrada Point in the San Rafael Swell of southeastern Utah. In the San Juan Basin, the Entrada is the basal formation of the San Rafael Group (Entrada Sandstone, Wanakah Formation, and Cow Springs Sandstone). The Entrada crops out around the basin margins and typically forms steep cliffs above the contact with the nonresistant Chinle Formation. The distinctive, bright-red cliffs along the northern side of Interstate 40 between Grants and Gallup are the Entrada Sandstone capped by the Todilto Limestone Member of the Wanakah Formation.

The Entrada Sandstone is present throughout the San Juan Basin and adjacent Colorado Plateau (Green and Pierson, 1977, p. 150, 151). Throughout most of the basin, the Entrada unconformably overlies the Chinle Formation (and equivalent rocks of the Dolores Formation in Colorado) except in the northwest, where it unconformably overlies the Wingate Sandstone. Rocks presently identified as Entrada along the southern margin of the basin originally were called Wingate Sandstone by Dutton (1885). Eventually, Baker and others (1947) revised the nomenclature and correlated the Entrada Sandstone of the stratotype in southeastern Utah with Dutton's (1885) Wingate Sandstone.

The Entrada Sandstone generally consists of reddish-orange, mottled red and white to light-brown silty sandstone and very fine to medium-grained well-sorted quartz sandstone interbedded with thinner reddish-brown siltstone (Smith, 1959, p. 74; O'Sullivan and Craig, 1973, p. 81; Green and Pierson, 1977, p. 151). High-angle, large-scale crossbedding is a characteristic feature, indicating deposition in an eolian environment, whereas the siltstone represents deposition in interdune and sabkha environments (Green and Pierson, 1977, p. 151).

In the southern and western parts of the San Juan Basin, the Entrada Sandstone has been divided into one formal and two informal members. In ascending order, these are the Iyanbito Member defined by Green (1974), the middle siltstone member, and the upper sandstone member (Green, 1974, fig. 2). The Iyanbito Member contains silty sandstone and crossbedded sandstone and is recognized only in the southern part of the basin, whereas the middle siltstone and upper sandstone members also are recognized in the western part of the basin. In the eastern and northern parts of the basin, the Entrada is undifferentiated (Green and Pierson, 1977, p. 151).

The thickness of the Entrada Sandstone is variable. Green and Pierson (1977, p. 151) reported a basinwide range in thickness of 60–330 feet. The maximum thickness is in the area north of Interstate 40 between Grants and Gallup (O'Sullivan and Craig, 1973, p. 81). Along the eastern basin margin, thickness ranges from about 100 feet near San Ysidro, N. Mex., to about 300 feet north of Cuba, N. Mex. (Woodward, 1987, p. 34). In the Four Corners area, along McElmo Creek north of Sleeping Ute Mountain in southwestern Colorado, the thickness is only 80–100 feet (Irwin, 1966, p. 18). Although not a productive aquifer, the Entrada has the potential of yielding small quantities of water to wells (Cooley and Weist, 1979, p. 58,59; Lyford, 1979, p. 6; Stone and others, 1983, p. 41).

WANAKAH FORMATION

Burbank (1930) defined the Wanakah Member of the Morrison Formation for exposures in the Wanakah mine near Ouray, Colo., north of Durango. Eckel (1949, p. 28–29) raised the Wanakah to formation rank and applied the name to strata between the Entrada and Junction Creek Sandstones. Strata equivalent to the Wanakah in northwestern New Mexico and northeastern Arizona, however, have had a problematic nomenclature history; in that region, the name Wanakah replaces the Summerville Formation and the upper part of the Bluff Sandstone (Condon and Huffman, 1988, p. 3; Condon, 1989a, p. 231). The Wanakah has limited potential as an aquifer (Cooley and Weist, 1979, p. 57, 58; Stone and others, 1983, p. 40); Thomas (1989) considered the formation to be a confining unit.

In New Mexico, the Wanakah Formation contains (in ascending order) the Todilto Limestone, Beclabito, and Horse Mesa Members (fig. 5) (Condon and Huffman, 1988, p. 3). In southwestern Colorado, the Wanakah consists of the basal part of the Pony Express Limestone (equivalent to the Todilto Limestone Member in New Mexico) and Bilk Creek Sandstone Members; a third member of informal usage, the marl member, also is present (Eckel, 1949, p. 28, 29). Molenaar (1989) recognized only the Pony Express Limestone Member and an informal upper member in Colorado (fig. 5).

The Todilto Limestone Member in New Mexico and equivalent Pony Express Limestone Member in Colorado are arbitrarily separated by the State line (Condon and Huffman, 1988, p. 5). These members contain two major lithofacies, a lower gray limestone unit and an upper gypsum and anhydrite unit (Green and Pierson, 1977, p. 151) and some siltstone and sandstone. The limestone facies is present throughout the study area except in the Gallup Sag and in the extreme northwest (Condon and Huffman, 1988, fig. A5). It conformably overlies the Entrada Sandstone and typically forms an erosion-resistant caprock. The maximum thickness of the limestone facies is about 40 feet (Green and Pierson, 1977, p. 151; Condon and Huffman, 1988, p. 5). The massive light-gray to white gypsum and anhydrite facies is present only in the eastern one-half of the study area (Condon and Huffman, 1988, fig. A5). Its thickness ranges from zero to a maximum of about 100 feet (Green and Pierson, 1977, p. 151). The Todilto Limestone and Pony Express Limestone Members were deposited either in a fresh to saline inland lake or in a restricted marine basin (Condon and Huffman, 1988, p. 5).

The Beclabito Member of the Wanakah Formation (Summerville Formation of former usage) is present throughout northeastern Arizona and northwestern New Mexico. This member was deposited either in a marginal lacustrine or marginal marine (sabkha) environment, depending on one's interpretation of the underlying Todilto Limestone and Pony Express Limestone Members (Green and Pierson, 1977, p. 151; Condon and Huffman, 1988, p. 7). The Beclabito Member conformably and gradationally overlies the Todilto Limestone and Pony Express Limestone Members and, in the western and southwestern part of the San Juan Basin, intertongues with the Cow Springs Sandstone (Condon and Peterson, 1986, fig. 4a; Condon and Huffman, 1988, fig. A3). The Beclabito Member consists of interbedded white to reddish-orange and reddish-brown claystone, massive or planar-bedded to crossbedded siltstone, and silty, very fine to fine-grained sandstone (Green and Pierson, 1977, p. 151; Condon and Huffman, 1988, p. 6). The basal part of the member grades into a coarse-grained fluvial conglomerate south and southeast of Grants. The Beclabito Member probably correlates with the Bilk Creek Sandstone Member and the marl member of the Wanakah Formation of southwestern Colorado (Condon and Huffman, 1988, p. 6–7). The thickness of the Beclabito Member ranges from about 125 to 200 feet (Condon and Huffman, 1988, p. 6).

The Horse Mesa Member of the Wanakah Formation (lower part of Bluff Sandstone of former usage) is present throughout northeastern Arizona and northwestern New Mexico. It represents deposition in eolian dune, interdune, localized fluvial, and sabkha environments (Condon and Huffman, 1988, p. 7). The Horse Mesa Member conformably overlies the Beclabito Member. Toward the east, it grades into the Beclabito Member, and toward the southwest it grades into the Cow Springs Sandstone (Condon and Peterson, 1986, fig. 4a; Condon and Huffman, 1988, p. 7, fig. A3; Condon, 1989b, fig. 2). The Horse Mesa Member mainly consists of cliff-forming, white to orange and red, planar-bedded and crossbedded, very fine to coarse-grained quartzose sandstone (Condon and Huffman, 1988, p. 7; Condon, 1989a, p. 235). The thickness of the Horse Mesa Member is about 40 feet at its stratotype. It thins to the north, grades laterally into the Cow Springs Sandstone to the south, has been removed by Cenozoic erosion to the west, and grades into the Baclabito Member in the subsurface to the east (Condon and Huffman, 1988, p. 7). Condon and Huffman (1988, p. 7) reported that the lower part of the Junction Creek Sandstone in southwestern Colorado probably correlates with the Horse Mesa Member.

COW SPRINGS SANDSTONE

The term Cow Springs Sandstone first appeared on a geologic section constructed by J.W. Harshbarger (in McKee, 1949, p. 46, fig. 6). The formation was named by Harshbarger and others (1951, p. 97) for exposures on the north face of Black Mesa near Cow Springs Trading Post, Coconino County, Ariz.

The Cow Springs Sandstone is present in the southwestern part of the San Juan Basin (Condon, 1989b, fig. 2), where its outcrops form prominent smooth and rounded cliffs. The Cow Springs intertongues with the Beclabito

Member of the Wanakah Formation throughout much of its extent and thins somewhat and intertongues with the Horse Mesa Member of the Wanakah Formation to the east and northeast (Condon and Huffman, 1988, p. 7; Condon, 1989b, fig. 2), forming a broad, vertical intergradational zone with the Wanakah Formation (Condon and Huffman, 1988, p. 7). The Cow Springs is conformably and gradationally overlain by the Recapture Member of the Morrison Formation (fig. 5) (Condon and Huffman, 1988, p. 7, figs. A2, A3). The upper part of the Cow Springs recently has been placed in the Recapture Member of the Morrison Formation and is now called the eolian facies of the Recapture Member (Condon, 1989a, p. 236). Cooley and Weist (1979, p. 56) reported that the Cow Springs yields some water to wells where it is hydraulically connected with the Morrison Formation in the southwestern part of the San Juan Basin. The Cow Springs is not present southwest of a lobate area approximately connecting the villages of Thoreau and Crystal, N. Mex. (Condon, 1989b, fig. 1).

The Cow Springs Sandstone represents deposition in eolian and interdune environments (Green and Pierson, 1977, p. 151). It mainly consists of crossbedded to flat-bedded, greenish-gray, light-yellowish-gray, and light-brown, well-sorted, fine- to medium-grained quartzose and arkosic sandstone; color banding is a characteristic feature (Harshbarger and others, 1951, p. 97; Green and Pierson, 1977, p. 151; Stone, 1979).

The thickness of the Cow Springs Sandstone at the stratotype is 342 feet (Harshbarger and others, 1951, p. 97). In the San Juan Basin, the maximum thickness is about 300 feet at Lupton, Ariz. The thickness decreases irregularly northward to about 200 feet south of Crystal and eastward to about 90 feet near Thoreau (Condon, 1989b, fig. 2).

JUNCTION CREEK SANDSTONE

The Junction Creek Sandstone has a history of nomenclature changes. The stratigraphic interval containing this formation was first identified by Cross and Purington (1899) as the La Plata Sandstone. Goldman and Spencer (1941) abandoned the term La Plata Sandstone and renamed its informal subdivisions as new lithostratigraphic units. Unit 5 was renamed the Junction Creek Sandstone Member of the Morrison Formation, represented by outcrops a few miles north of Durango (Goldman and Spencer, 1941, p. 1750, 1751). Eckel (1949, p. 1) abandoned the member status of the Junction Creek and interpreted it to be a separate formation. Craig and Cadigan (1958, p. 182) stated that the Junction Creek Sandstone of southwestern Colorado directly correlates with the Bluff Sandstone of southeastern Utah. Irwin (1966, p. 20) also correlated the Junction Creek with the Bluff Sandstone and attributed confusion with terminology to problems at the Colorado-Utah State line. O'Sullivan (1980) reassigned the Bluff Sandstone of southeastern Utah and northeastern Arizona to member status in the Morrison Formation, and Condon and Huffman (1988, p. 10) stated that the Bluff Sandstone Member and Junction Creek Sandstone are correlative.

The Junction Creek Sandstone has been mapped only in southwestern Colorado, in the northern part of the San Juan Basin (Haynes and others, 1972; Steven and others, 1974). The formation, however, reportedly continues southward in the subsurface for several townships into New Mexico (Steven M. Condon, U.S. Geological Survey, oral commun., 1989). Stone and others (1983, sheet 4) also showed the Junction Creek as extending several miles into New Mexico in the subsurface. The Junction Creek yields small amounts of water to wells, mainly in southwestern Colorado, and is hydraulically connected with the Morrison Formation (Cooley and Weist, 1979, p. 57).

The Junction Creek Sandstone typically forms prominent smooth and rounded cliffs; locally, it weathers to hoodoo forms (Ekren and Houser, 1958, p. 74). The Junction Creek conformably or gradationally overlies the Wanakah Formation (fig. 5) (Eckel, 1949, p. 29) and is conformably or gradationally overlain by the Morrison Formation.

The Junction Creek Sandstone was deposited in an eolian environment (Haynes and others, 1972). The major part of the formation consists of crossbedded, white to buff, light-brownish-gray, pink, or reddish-orange, poorly sorted, fine- to coarse-grained quartzose sandstone (Irwin, 1966, p. 20, 21; Haynes and others, 1972). Thinner lenticular, horizontally bedded, arkosic sandstone beds and partings of gray or red shale also are present (Eckel, 1949, p. 29).

The thickness of the Junction Creek Sandstone is variable, ranging from 200 to 500 feet in southwestern Colorado (Goldman and Spencer, 1941, p. 1750; Eckel, 1949, p. 29). Irwin (1966, p. 21, 22) reported a range of 230–300 feet on the Ute Mountain Ute Indian Reservation and the thinning of the unit southward into New Mexico. Haynes and others (1972) stated that the Junction Creek in southwestern Colorado thins eastward and that toward the north, it merges with the upper part of the underlying Summerville Formation (now Wanakah Formation; fig. 5).

MORRISON FORMATION

The Morrison Formation was named by G.H. Eldridge (in Emmons and others, 1894) for exposures near the town of Morrison, Jefferson County, Colo., about 10 miles southwest of Denver. Major sandstones in the Morrison typically form erosion-resistant cliffs and dip slopes, whereas shales form topographic saddles and slopes.

The Morrison Formation is present throughout the San Juan Basin (pl. 1) (Green and Pierson, 1977, p. 151) and crops out around the basin margins. It conformably overlies the Wanakah Formation and Cow Springs Sandstone (Condon and Peterson, 1986, p. 24). In the northern part of the basin, the Morrison conformably overlies and probably intertongues with the Junction Creek Sandstone (fig. 5). The Morrison is disconformably overlain by the Dakota Sandstone throughout most of the San Juan Basin except the northern part, where it is conformably overlain by and locally intertongues with the Burro Canyon Formation (fig. 5) (Green and Pierson, 1977, p. 151).

The Morrison Formation generally consists of yellowish-tan to pink, fine- to coarse-grained, locally conglomeratic sandstone that is interbedded with sandy siltstone and green to reddish-brown shale and claystone; minor limestone beds also are present (Woodward and Schumacher, 1973, p. 3–5; Green and Pierson, 1977, p. 151; Stone and others, 1983, p. 38). Morrison strata were deposited in various continental environments including stream channels, flood plains, and lakes (Green and Pierson, 1977, p. 151).

In the San Juan Basin, the Morrison Formation consists of five members (Gregory, 1938; Craig and others, 1955; Cadigan, 1967; Green and Pierson, 1977; Owen, 1984). In ascending order, they are the Salt Wash Member, Recapture Member, Westwater Canyon Member, Brushy Basin Member, and Jackpile Sandstone Member.

The most prolific regional aquifers in the San Juan Basin are in the Morrison Formation, particularly in the Westwater Canyon Member. Although coarser grained units within each member of the Morrison are aquifers, shaly and clayey zones within the members act as confining units. Several authors have reported on the hydrogeologic characteristics of the Morrison (Kelly, 1977; Cooley and Weist, 1979, p. 54, 55; Lyford, 1979, p. 8; Stone and others, 1983, p. 38, 39; Dam and others, 1990a). Kelly (1977) detailed the hydrogeology of the Westwater Canyon Member in the southern part of the basin. Dam and others (1990a) discussed the hydrogeology of the Morrison throughout the basin. The Westwater Canyon Member also is the major uranium-bearing formation in the basin.

The Salt Wash Member of the Morrison Formation is present only in the northern and northwestern parts of the San Juan Basin (Craig and others, 1955, fig. 21; Condon and Peterson, 1986, p. 21). It forms ledgy slopes and mainly consists of white to grayish-yellow and pale-orange, crossbedded, fine- to medium-grained and locally conglomeratic fluvial sandstone. The sandstone may be present either as individual lenses that are as much as 20 feet thick or as stacked beds as much as 80 feet thick. Interbedded with the sandstone are reddish-brown, grayish-red, and greenish-gray silty claystones that locally contain platy or slabby gray limestone beds (Craig and others, 1955, p. 135, 136). The Salt Wash Member mainly was deposited in a fluvial environment, but it also contains minor eolian sandstone and lacustrine limestone beds (Condon and Peterson, 1986, p. 21). The maximum thickness of the Salt Wash Member in the San Juan Basin is about 200 feet near the Four Corners. Southeastward, 30–50 miles into New Mexico, the Salt Wash Member intertongues with and pinches out in the overlying Recapture Member (Craig and others, 1955, p. 137, fig. 21).

The Recapture Member of the Morrison Formation is present throughout much of the San Juan Basin (Craig and others, 1955, fig. 22) as the lower part of the Morrison Formation. Recent revisions in nomenclature and in the definition of the Recapture have extended this member southward from its original limit (Condon and Peterson, 1986, p. 21, 22; Condon, 1989a, p. 236, 237). The Recapture Member recently has been subdivided into two major facies: the lower eolian facies and the upper fluvial facies (Condon and Peterson, 1986, p. 21). The eolian facies forms cliffs or steeper slopes than does the fluvial facies, which forms varicolored slopes. Generally, the eolian facies is dominant in the southern and southwestern parts of the basin and the fluvial facies is dominant in the northwest (Condon and Peterson, 1986, p. 22). The eolian facies has previously been called the Cow Springs Sandstone, Zuni Sandstone, or upper part of the Bluff Sandstone (Condon and Peterson, 1986, p. 21). It is characterized by large-scale crossbedding consisting of light-brown, yellowish-gray, or pale-red, fine- to medium-grained sandstone; locally, claystone and siltstone beds are present. The thickness of the eolian facies ranges from 75 to 300 feet (Condon and Peterson, 1986, p. 21). Condon (1989a, p. 237) considered the eolian facies of the Recapture to be time equivalent to the Bluff Sandstone Member of the Morrison Formation in southeastern Utah and the Junction Creek Sandstone in southwestern Colorado. South of the San Juan Basin, the Recapture Member is disconformably truncated by the Dakota Sandstone erosion surface (Craig and others, 1955, fig. 22; Condon, 1989a, p. 237).

The fluvial facies of the Recapture Member constitutes the classic description of the member in previous geologic literature (prior to the report by Condon and Peterson, 1986). It mainly consists of pale-red to grayish-red, silty and sandy claystone interbedded with some light-brown to pinkish-gray, fine- to medium-grained sandstone (Craig and others, 1955, p. 140); gray limestone beds also are present locally (Woodward and Schumacher, 1973, p. 3). The thickness of the fluvial facies in the San Juan Basin varies from 40 to 370 feet on the east side, to about 200 feet on the south side, to between 200 and 500 feet on the west side; the facies pinches out south of Grants (Condon and Peterson, 1986, p. 21). In the Cuba area, it cannot be differentiated from the Beclabito Member of the Wanakah Formation, which prompted Woodward and Schumacher (1973, p. 3) to call it the lower member of the Morrison Formation.

The Westwater Canyon Member of the Morrison Formation typically forms cliffs or ledgy slopes. This member was deposited by a braided-stream complex and consists of yellowish-gray to tan, pink or light-brown, fine- to coarse-grained locally conglomeratic sandstone interbedded with shale or claystone (Craig and others, 1955, p. 153; Woodward and Schumacher, 1973, p. 3). Grain size increases toward the west-central part of the basin until the member consists wholly of conglomeratic sandstone (Craig and others, 1955, p. 154). The thickness of the Westwater Canyon Member increases from about 100 feet on the north, east, and south sides of the San Juan Basin to about 300 feet in the west-central part of the basin (Craig and others, 1955, p. 154).

The Brushy Basin Member of the Morrison Formation is present throughout the San Juan Basin (Craig and others, 1955, fig. 29). This member consists of variegated (green, reddish-brown, and grayish-purple) calcareous and bentonitic claystone and mudstone of lacustrine origin that form slopes in the outcrop. Fluvial deposits of light-brown to yellowish-gray, fine- to medium-grained sandstone, and locally thin beds of limestone deposited in freshwater lakes also are present (Craig and others, 1955, p. 156; Condon and Peterson, 1986, p. 22). The thickness of the Brushy Basin Member ranges from about 150 feet along the northern and eastern basin margins to about 250 feet in the Central Basin. In the Defiance Uplift area, the thickness ranges from zero to about 100 feet. Along the southern basin margin, the Brushy Basin Member is disconformably overlain by the Dakota Sandstone (Craig and others, 1955, p. 156, fig. 29).

The Jackpile Sandstone Member of the Morrison Formation (Owen, 1984, p. 45) is found mostly in the southeastern part of the San Juan Basin and crops out discontinuously between the villages of Laguna and Cuba, N. Mex. The Jackpile Sandstone Member is present in the subsurface as far north as the Chaco Culture National Historical Park area (Owen, 1984, fig. 9). It forms cliffs or ledgy slopes and gradationally or disconformably overlies the Brushy Basin Member and is in turn disconformably overlain by the Dakota Sandstone (fig. 5). The Jackpile Sandstone Member is lithologically similar to and occupies the same stratigraphic horizon as the Burro Canyon Formation to the north (Aubrey, 1988, p. 62). The Jackpile Sandstone Member was deposited by a braided-stream system and mainly consists of white to yellowish-tan, crossbedded, medium- to coarse-grained, locally conglomeratic arkosic sandstone; lenses of variegated (red to pale-green) bentonitic mudstone also are present locally (Owen, 1984, p. 46–51). The average thickness in the vicinity of the stratotype (the Jackpile-Paguate uranium mine north of Laguna) is about 100 feet with a maximum of about 300 feet. South of the stratotype, the thickness decreases to zero because of disconformable truncation by the Dakota Sandstone (Owen, 1984, p. 50).

The thickness of the Morrison Formation in the San Juan Basin ranges from about 200 feet near Grants to about 1,100 feet in the northwestern part of the basin. The greatest thickness is in a north-northwest-trending zone from southeast of Crownpoint, N. Mex., to Cortez, Colo. (fig. 9).

The depth to the top of the Morrison Formation ranges from zero in areas of outcrop to about 8,500 feet below land surface in the northeastern part of the study area (fig. 10). The rapid increase in depth in the area northeast of Grants is due to the local topography of Mount Taylor.

The altitude and configuration of the top of the Morrison Formation is shown in figure 11. Because the top of the Morrison is a key marker horizon throughout the San Juan structural basin, figure 11 also illustrates the overall structural configuration of the basin. The top of the Morrison decreases from a maximum altitude of about 10,000 feet above sea level on the outcrops along the northern basin margin near Durango to about 1,500 feet below sea level in the subsurface beneath Navajo Reservoir in the northeastern part of the study area.

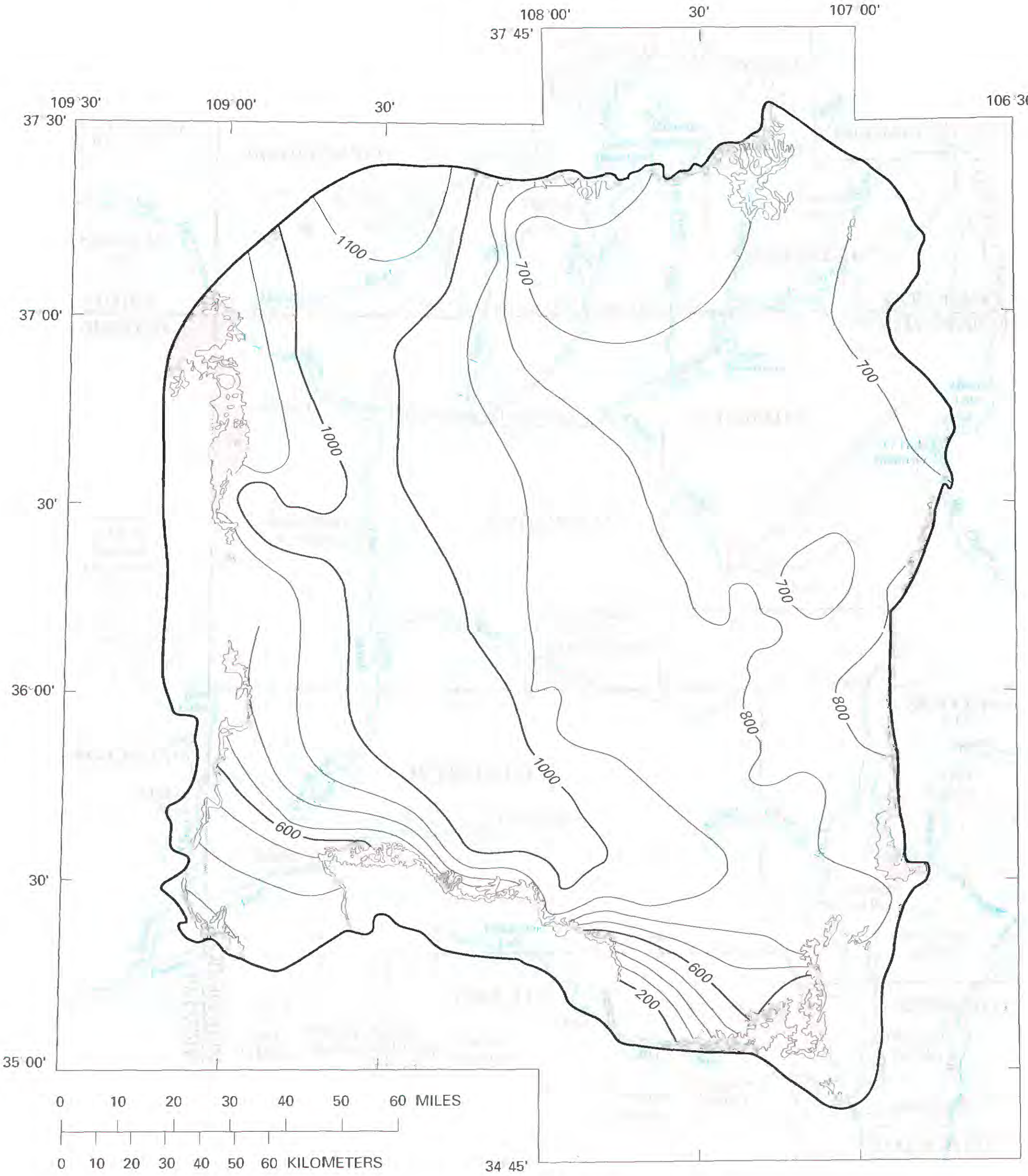
CRETACEOUS ROCKS

Sedimentary rocks of Cretaceous age in the San Juan structural basin (in ascending order) consist of the Burro Canyon Formation, Dakota Sandstone, Mancos Shale, Gallup Sandstone, Crevasse Canyon Formation, Point Lookout Sandstone, Menefee Formation, Cliff House Sandstone, Lewis Shale, Pictured Cliffs Sandstone, Fruitland Formation, and Kirtland Shale. All are of Late Cretaceous age with the exception of the Burro Canyon Formation, which is Early Cretaceous.

Cretaceous rocks mainly consist of transgressive and regressive marine shore-zone sediments that were deposited in shallow seas that encroached into the San Juan Basin area from the northeast, and also nonmarine clastic deposits from source areas southwest of the basin. Several transgressions and regressions of the shallow seas occurred during Late Cretaceous time, and the area has been referred to by Fassett (1974, p. 225) as the SCI–SWO (sea came in-sea went out) zone. Molenaar (1977b, p. 159, 160) presented a concise summary of the depositional history of the San Juan Basin during the Late Cretaceous, an epoch in which at least 6,500 feet of sediments were deposited. The general lithologies and thicknesses of Cretaceous rocks are summarized in table 1; outcrops of these rocks are shown on plate 1.

BURRO CANYON FORMATION

The Burro Canyon Formation was named by Stokes and Phoenix (1948) for exposures in Burro Canyon, just east of the Dolores River in San Miguel County, Colo. The Burro Canyon mainly is present in southwestern Colorado, but lenses of the formation also are present in northwestern New Mexico, northeastern Arizona, and southeastern Utah (Ekren and Houser, 1959, p. 200). The Burro Canyon typically is mapped with the Dakota Sandstone; however, locally it can be mapped separately (Haynes and others, 1972; Steven and



EXPLANATION

Outcrops of Morrison Formation—From Dane and Bachman (1965), Wilson and others (1969), Tweto (1979), and Hintze (1981)

Outcrops of Zuni Sandstone (of former usage)—From Dane and Bachman (1965). Now included in Morrison Formation (Condon, 1989a, b)

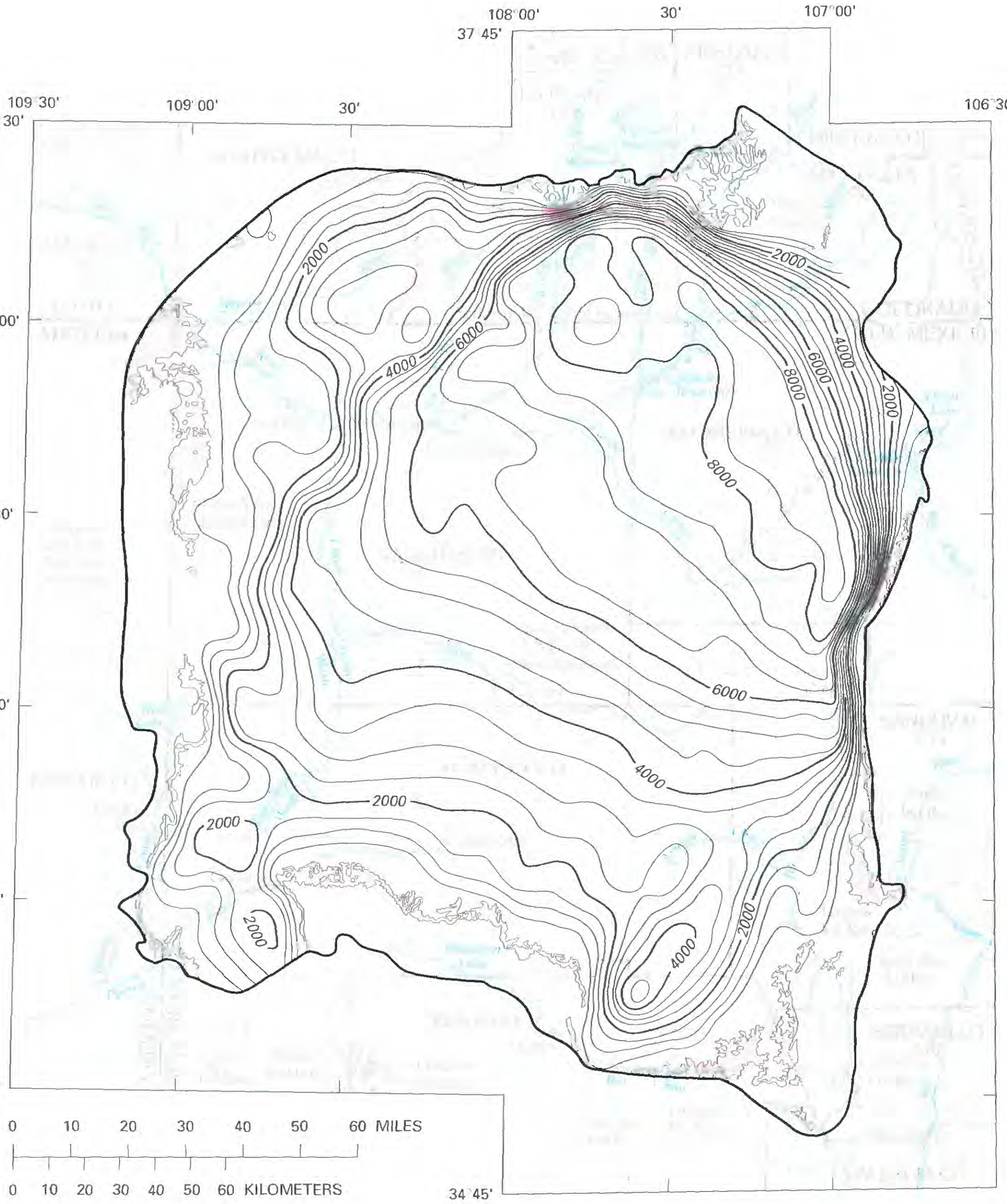
Outcrops of Morrison and Wanakah Formations and Entrada Sandstone, undivided—From Tweto (1979)

Outcrops of Morrison Formation and San Rafael Group, undivided—From Wilson and others (1969)

Boundary of study area

1000 **Line of equal approximate thickness of Morrison Formation**—Interval 100 feet

FIGURE 9.—Approximate thickness of the Morrison Formation in the San Juan Basin study area. Modified from Dam and others (1990a).



EXPLANATION

Outcrops of Morrison Formation—From Dane and Bachman (1965), Wilson and others (1969), Tweto (1979), and Hintze (1981)

Outcrops of Zuni Sandstone (of former usage)—From Dane and Bachman (1965). Now included in Morrison Formation (Condon, 1989a, b)

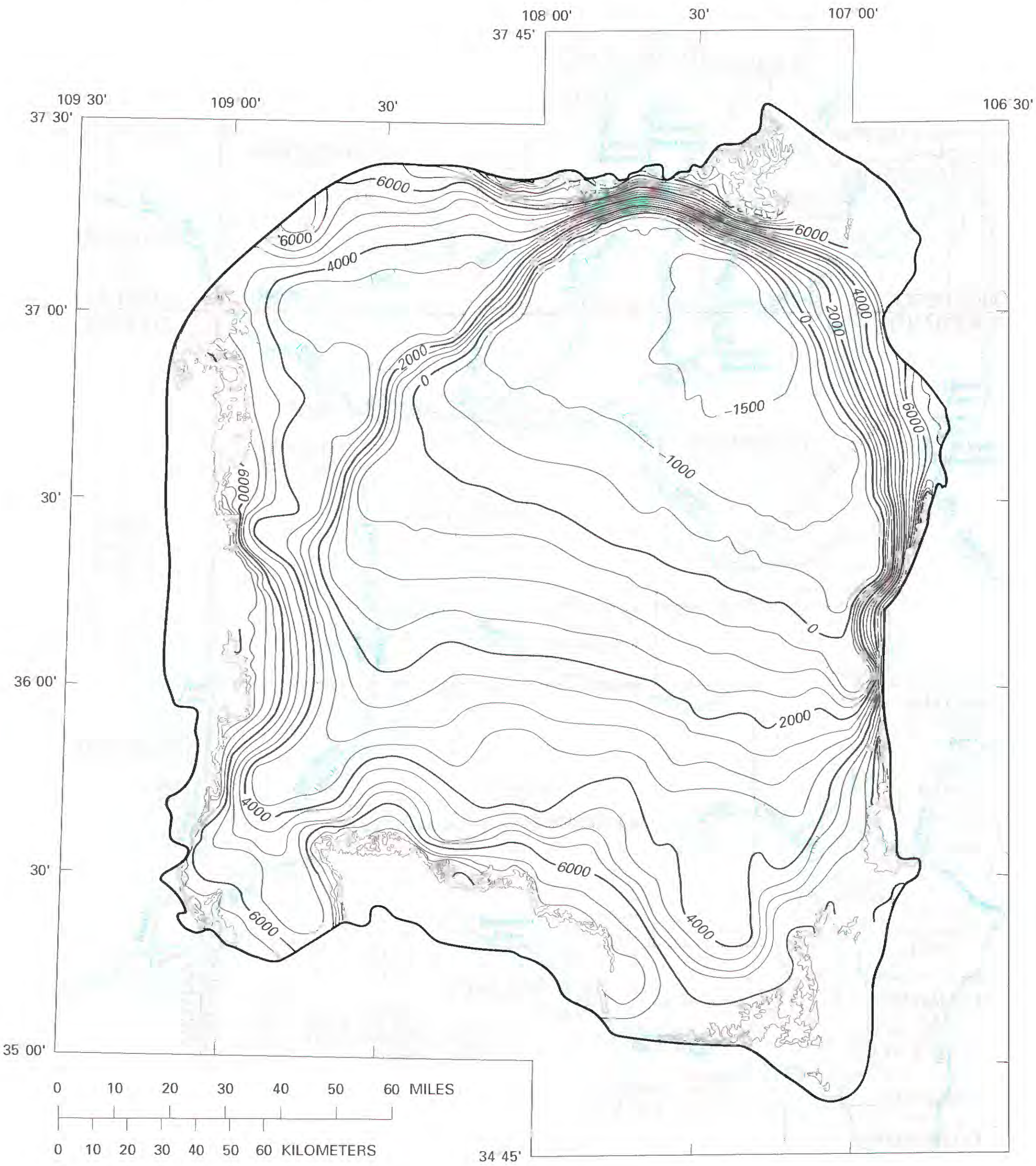
Outcrops of Morrison and Wanakah Formations and Entrada Sandstone, undivided—From Tweto (1979)

Outcrops of Morrison Formation and San Rafael Group, undivided—From Wilson and others (1969)

Boundary of study area

2000 **Line of equal depth to top of Morrison Formation**—Interval 500 feet. Datum is land surface

FIGURE 10.—Approximate depth to the top of the Morrison Formation in the San Juan Basin study area. Modified from Dam and others (1990a).



EXPLANATION

Outcrops of Morrison Formation—From Dane and Bachman (1965). Wilson and others (1969). Tweto (1979). and Hintze (1981)

Outcrops of Zuni Sandstone (of former usage)—From Dane and Bachman (1965). Now included in Morrison Formation (Condon. 1989a. b)

Outcrops of Morrison and Wanakah Formations and Entrada Sandstone, undivided—From Tweto (1979)

Outcrops of Morrison Formation and San Rafael Group, undivided—From Wilson and others (1969)

Boundary of study area

—*2000*— **Structure contour**—Shows altitude of top of Morrison Formation. Contour interval 500 feet. Datum is sea level

FIGURE 11.—Approximate altitude and configuration of the top of the Morrison Formation in the San Juan Basin study area. Modified from Dam and others (1990a).

others, 1974). Irwin (1966, p. 26) reported that the Burro Canyon either is absent or cannot be recognized south of the San Juan River in New Mexico. The Burro Canyon is present in the Chama Embayment, which is adjacent to the northeastern margin of the San Juan Basin (fig. 2), but whether it is present in the northeastern part of the San Juan Basin has been the subject of some debate (Saucier, 1974, p. 212–215; Owen and Siemers, 1977, p. 179, 180; Anderholm, 1979, p. 44; Woodward, 1987, p. 35; Aubrey, 1988, fig. C2). A conglomeratic sandstone does persist at the base of the Dakota Sandstone in this area, but whether it belongs in the Dakota or the Burro Canyon is still open to discussion.

Throughout its extent, the Burro Canyon Formation conformably overlies the Brushy Basin Member of the Morrison Formation (fig. 5) and probably represents a continuation of deposition from Late Jurassic through Early Cretaceous time. Ekren and Houser (1959, p. 192, 193) reported that locally in the Four Corners area, Burro Canyon sandstone lenses intertongue with mudstone of the Brushy Basin Member. The Burro Canyon is disconformably overlain by the Dakota Sandstone (fig. 5).

Strata of the Burro Canyon Formation were deposited in various fluvial environments such as streams and flood plains (Ekren and Houser, 1965, p. 18). Ridgley (1977, p. 157, 158) reported that the lower part of the Burro Canyon was deposited by a series of high-energy braided to meandering streams, whereas the upper part of the formation was deposited by low-energy, meandering streams.

Lithologically, the Burro Canyon Formation consists of lenticular, white, light-gray, and pale-brown to tan, fine- to coarse-grained sandstone and conglomeratic channel sandstone. These sandstone lenses are quartzose and kaolinitic, with pebbles of varicolored chert. The lenses commonly are crossbedded and vertically stacked, forming rough ledges and cliffs. Interbedded with the sandstone are greenish-gray and reddish-brown shale and mudstone. Southward, the sandstone becomes thinner and discontinuous and mudstone beds become predominant (Ekren and Houser, 1959, p. 194, 195; and 1965, p. 18, 19; Irwin, 1966, p. 26–28).

The thickness of the Burro Canyon Formation is variable. In the Sleeping Ute Mountain area, it ranges from 30 to 200 feet (Ekren and Houser, 1965, p. 18), averaging about 150 feet in the general northwestern part of the San Juan Basin (Haynes and others, 1972). Southward, toward the San Juan River, the Burro Canyon thins to an irregular pinch-out edge, after which only a few discontinuous lenses of conglomeratic sandstone are found; the unit also thins toward the northeast to a series of discontinuous mudstone and sandstone lenses (Haynes and others, 1972). The Burro Canyon yields small quantities of water to wells and springs (Cooley and Weist, 1979, p. 53).

DAKOTA SANDSTONE

The Dakota Sandstone generally is thought to be of earliest Late Cretaceous age, although the lowermost part may be of latest Early Cretaceous age (Fassett, 1974, p. 225). The formation crops out around the basin margins (pl. 1), where it typically caps mesas and forms erosion-resistant dip slopes and hogbacks.

The Dakota Sandstone in the San Juan Basin and vicinity was deposited on a regional erosion surface; the strata represent a transition from continental alluvial-plain deposition in the lower part of the formation to marine shore-zone deposition in the upper part. Owen (1973, p. 39–51) presented a comprehensive depositional model for the formation in the San Juan Basin. The Dakota disconformably overlies the Brushy Basin Member of the Morrison Formation throughout much of the basin. However, it also disconformably overlies the Westwater Canyon Member of the Morrison in the southwest, the Jackpile Sandstone Member of the Morrison in the southeast, as well as the Burro Canyon Formation in the north (fig. 5). The upper contact of the Dakota Sandstone is conformable with the Mancos Shale, and intertonguing of these two formations is common near the contact.

The stratigraphy of the Dakota Sandstone is complex. The formation consists of a main sandstone body in the north that branches into members and tongues in the rest of the San Juan Basin. The Dakota consists of five formal subdivisions (Landis and others, 1973; Owen, 1973; Aubrey, 1988, p. 59); in ascending order, these are the Encinal Canyon Member, Oak Canyon Member, Cubero Tongue, Paguate Tongue, and Twowells Tongue. The two upper members intertongue with the Graneros Member of the Mancos Shale.

The Dakota Sandstone contains three principal lithologies: a sequence of buff to brown, crossbedded, poorly sorted, coarse-grained conglomeratic sandstone and moderately sorted, medium-grained sandstone in the lower part; dark-gray carbonaceous shale with brown siltstone and lenticular sandstone beds in the middle; and yellowish-tan, fine-grained sandstone interbedded with gray shale in the upper part (Owen, 1973, p. 39–48; Merrick, 1980, p. 45–47).

The thickness of the Dakota Sandstone has an overall range of a few tens of feet to about 500 feet; Stone and others (1983, p. 37) reported that 200–300 feet probably is the most common range. Data reported by Molenaar (1977b, p. 160, 161) and Stone and others (1983, fig. 66), along with data obtained from Petroleum Information Corporation, indicate that the thickness of the Dakota generally increases from the northern, northwestern, and western margins of the basin toward the southern, southeastern, and eastern margins.

The depth to the top of the Dakota Sandstone ranges from outcrops around the basin margins to about 8,500 feet in the northeastern part of the study area (fig. 12). The rapid increase in depth in the area northeast of Grants reflects the local topography of Mount Taylor.

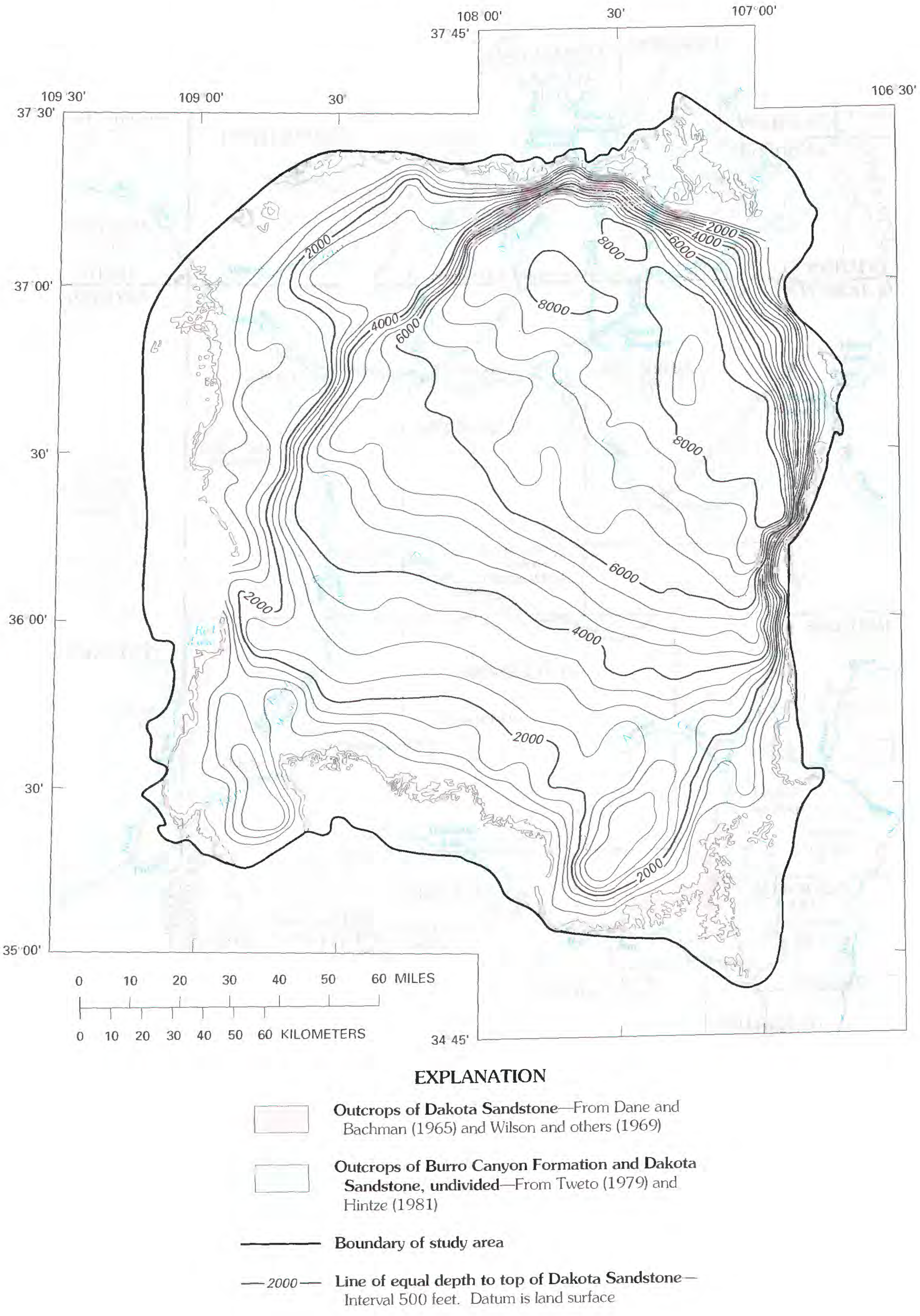


FIGURE 12.—Approximate depth to the top of the Dakota Sandstone in the San Juan Basin study area. Modified from Craigg and others (1989).

The altitude and configuration of the top of the Dakota Sandstone are shown in figure 13. The top of the Dakota decreases from a maximum altitude of about 9,500 feet above sea level on the outcrops along the northern basin margin near Vallecito Reservoir in Colorado, to about 1,500 feet below sea level in the subsurface beneath Navajo Reservoir in the northeastern part of the study area. Because the Dakota is a key marker zone in the San Juan Basin, the overall structural configuration of the basin also is reflected in figure 13.

The Dakota Sandstone forms a dependable aquifer throughout much of the San Juan Basin, but well yields generally are small. Locally, in the southern part of the basin, the Dakota is hydraulically connected with the underlying Morrison Formation (Cooley and Weist, 1979, p. 52, 53; Stone and others, 1983, p. 37, 38; Craigg and others, 1989).

MANCOS SHALE

The Mancos Shale was named by Cross and Purington (1899) for characteristic exposures in the Mancos River valley near Mesa Verde National Park, Colo. Topography formed by the Mancos typically is rolling to flat, rough and broken, and has a badlands appearance. Localized, erosion-resistant siltstone, sandstone, or limestone caps isolated buttes or hillocks, whereas softer shale forms slopes and broad valleys or flats. The Mancos commonly forms steep slopes below mesas or buttes capped by Upper Cretaceous regressive marine sandstones (Gallup Sandstone, Dalton Sandstone Member of the Crevasse Canyon Formation, and Point Lookout Sandstone; fig. 5).

Basinwide, the Mancos Shale conformably overlies and intertongues with the transgressive marine Dakota Sandstone (fig. 5) and is conformably overlain by and intertongues with the regressive marine Point Lookout Sandstone. In the southwestern part of the basin, the Mancos intertongues with the regressive marine Gallup Sandstone. In the extreme southern part of the basin, the Mancos locally intertongues with the Dalton Sandstone Member of the Crevasse Canyon Formation, a local regressive marine sandstone, and the Hosta Tongue of the Point Lookout Sandstone, a local transgressive marine sandstone.

The Mancos Shale is present throughout the San Juan Basin and comprises most of the Upper Cretaceous marine deposits (pl. 1). It was deposited in relatively shallow offshore marine environments, possibly no more than 400 feet deep (Molenaar, 1977b, p. 161). In general, the Mancos consists of gray to black shale and claystone with discontinuous yellowish-gray, calcareous siltstone and sandstone (O'Sullivan and Beikman, 1963; Haynes and others, 1972; Steven and others, 1974; Hackman and Olson, 1977). Thin bentonite beds are common in the lower part of the formation (Wyant and Olson, 1978). The Mancos also contains zones of calcareous concretions, some thin limestone beds, and offshore sandstone bar deposits (Molenaar, 1977b, p. 161). Cooley and Weist (1979, p. 50) reported that the Mancos contains more sandstone in the southern and western parts of the basin, and more limestone and calcareous shale in the northern and northeastern parts of the basin. Regionally, the Mancos is a confining unit, but locally, sandstone bodies within the formation yield small quantities of water to wells (Craigg, 1980, p. 57, 58).

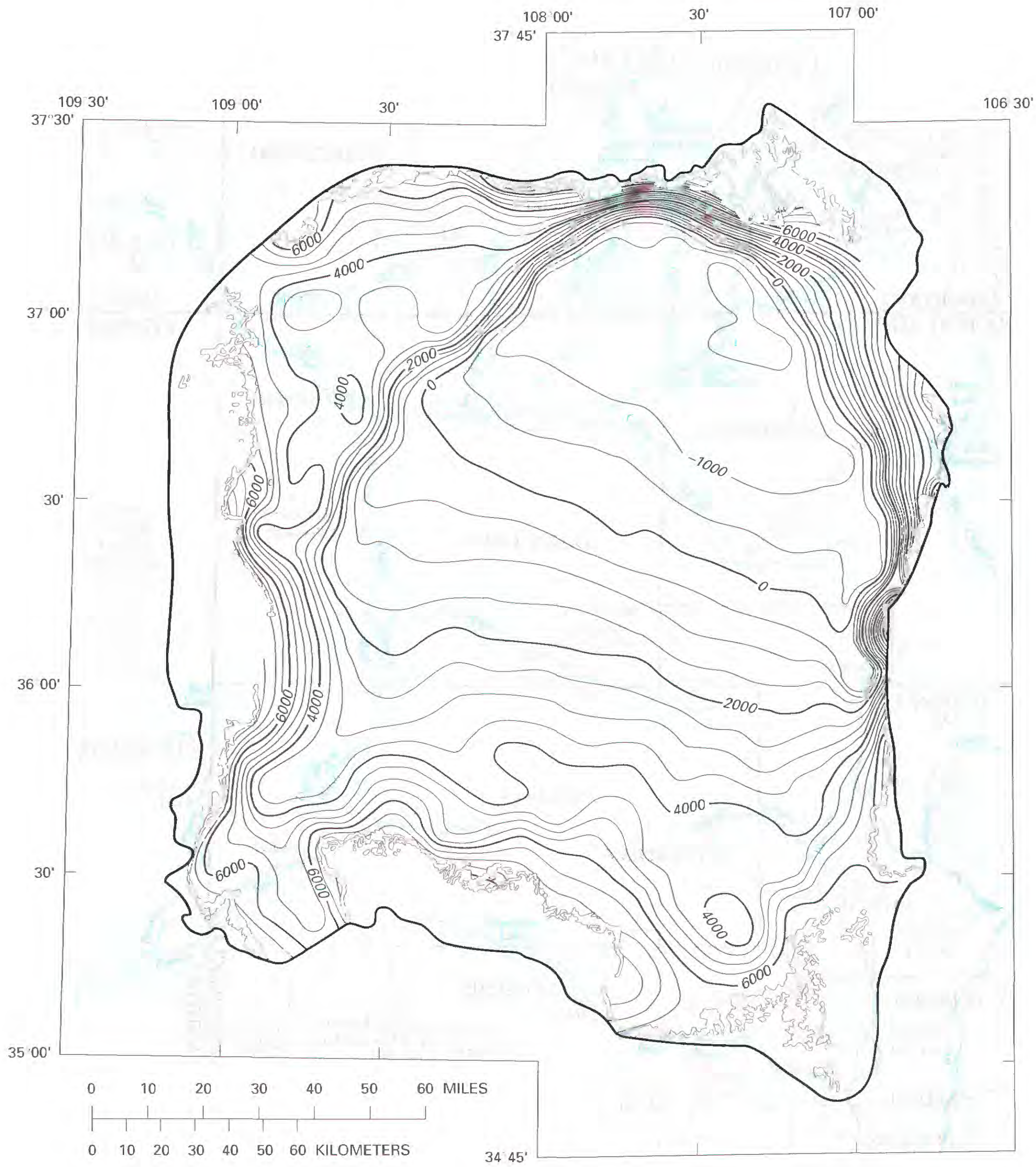
The Mancos Shale consists of a main body in the north that attains a maximum thickness of about 2,300 feet (Molenaar, 1977a, 1989) from which several members or tongues extend to the southwest. These are the Graneros, Bridge Creek (formerly Greenhorn) Limestone, Semilla Sandstone, Juana Lopez, and El Vado Sandstone Members; the Tocito Sandstone Lentil; the Pescado Tongue (a localized tongue in the southwestern part of the basin), and the Mulatto and Satan Tongues. Fassett (1974) and Molenaar (1977b, 1983) presented concise summaries of the geologic characteristics of these rocks.

GALLUP SANDSTONE

The Gallup Sandstone has a smaller areal extent than the other major Upper Cretaceous sandstones in the San Juan Basin and is present only in New Mexico and a small part of Arizona. The Gallup crops out in an arcuate pattern around the margins of the southwestern part of the basin (pl. 1) where the formation typically forms erosion-resistant cliffs and dip slopes.

As originally defined by Sears (1925) and discussed in detail by Dane and others (1957) and Molenaar (1973, 1974, 1983), the Gallup Sandstone actually consists of several rock types including conglomerate, sandstone (the predominant lithology), shale, carbonaceous shale, and coal. The interval delineated by these rocks represents the first major regression of the Late Cretaceous sea in the San Juan Basin area. The strata indicate deposition in various marine and nonmarine environments including shore zone, transitional offshore, coal swamp, fluvial and distributary channel, and eolian dune (Molenaar, 1973, 1974, 1983; Campbell, 1979).

The Gallup Sandstone is restricted to the southwestern one-half of the San Juan Basin, partly because of stratigraphic pinch out and partly because of truncation (figs. 5 and 14) (Molenaar, 1973, p. 85). From its outcrops, the Gallup dips toward the center of the basin and terminates in a northwest-trending truncation line that extends from the southeastern part of the basin, through the central part, to the area northwest of Shiprock (fig. 15). The Gallup is not present beyond this truncation line, which is a pre-Niobrara erosion surface (Penttila, 1964; Molenaar, 1973, 1974, 1983). Molenaar (1973, p. 85) reported that as much as 300 feet of



EXPLANATION

Outcrops of Dakota Sandstone—From Dane and Bachman (1965) and Wilson and others (1969)

Outcrops of Burro Canyon Formation and Dakota Sandstone, undivided—From Tweto (1979) and Hintze (1981)

Boundary of study area

2000 **Structure contour**—Shows altitude of top of Dakota Sandstone. Contour interval 500 feet. Datum is sea level

FIGURE 13.—Approximate altitude and configuration of the top of the Dakota Sandstone in the San Juan Basin study area. Modified from Craigg and others (1989).

Upper Cretaceous strata has been removed northeast of this truncation line.

Isolated marine sandstone lenses are present in the transgressive Mulatto Tongue of the Mancos Shale northeast of the truncation line. These lenses have been referred to by informal names such as basal Niobrara sandstone, transgressive Gallup sandstone, Tocito sandstone, and Stray sandstone; they are now formally named Tocito Sandstone Lentils of the Mancos Shale (Molenaar, 1983, p. 38). Many of these lenticular sandstones are found at stratigraphic horizons that suggest the presence of the Gallup Sandstone (Molenaar, 1973, 1974, 1983; Kernodle and others, 1989), and some authors have suggested that the Gallup is present throughout the San Juan Basin (for example, see Miller and others, 1990). The Tocito Sandstone Lentils, however, are not connected with or depositionally related to the Gallup Sandstone (Molenaar, 1973, 1974).

As noted by several authors (Beaumont, 1957; Budd, 1957; Dane and others, 1957; Molenaar, 1973, 1974, 1983; and Campbell, 1979), the stratigraphy of the Gallup Sandstone is complex. The stratigraphic relations are complicated by numerous facies changes within the formation, intertonguing with adjacent rocks, and thinning and erosional truncation toward the basin center. Nonuniform and inconsistent geologic names also have complicated the stratigraphic interpretations of the Gallup. In detailed stratigraphic studies, Molenaar (1973) identified seven regional sandstone bodies in the interval referred to as the Gallup Sandstone. He proposed that the uppermost of these (a fluvial sandstone) be called the Torrivio Sandstone Member; the remaining six sandstone bodies were informally referred to using letter designations A through F. Mizell and Stone (1979) published maps showing the areal extent and thickness of these sandstone bodies. Molenaar (1983), in a classic stratigraphic paper, established the principal reference section for the Gallup, revised the stratigraphic nomenclature of this interval, and formally named the uppermost nonmarine sandstone body the Torrivio Member. The complex stratigraphic relations within the Gallup Sandstone and its relation to adjacent rocks are shown diagrammatically in figure 14.

Throughout its extent, the Gallup Sandstone conformably overlies and intertongues with the lower part of the Mancos Shale (fig. 14). Along its outcrop belt and throughout the southwestern part of the basin, the Gallup is conformably overlain and intertongues with the Dilco Coal Member of the Crevasse Canyon Formation. Regressive deposits of the Gallup grade seaward (northeast) into offshore deposits of the lower part of the Mancos and grade landward (southwest) into

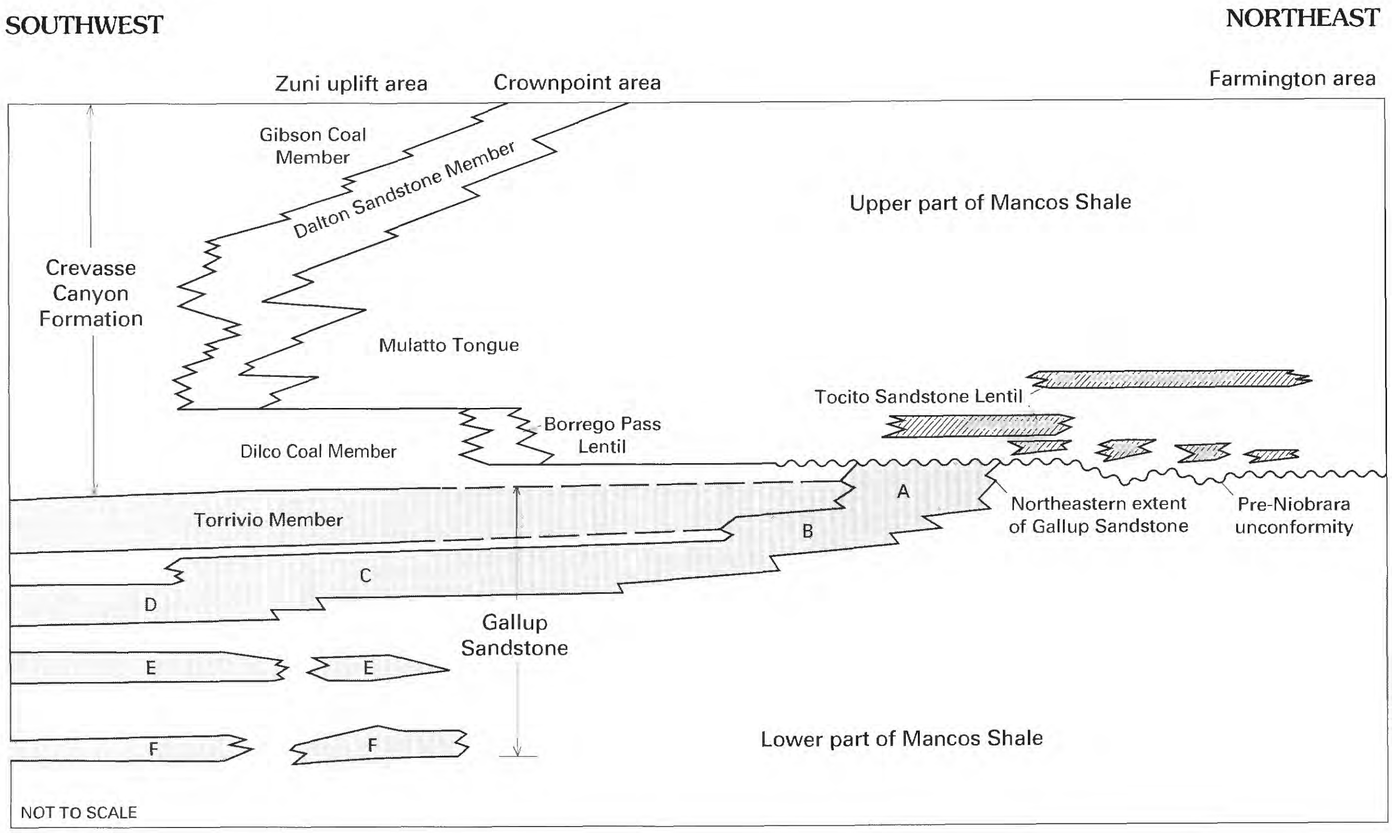


FIGURE 14.—Diagrammatic subsurface stratigraphic correlation of the Gallup Sandstone and adjacent units in New Mexico. Modified from Molenaar (1973, 1974, and 1983).

nonmarine deposits of the Crevasse Canyon. Beginning a few miles northeast of the town of Gallup, the basal transgressive marine Mulatto Tongue of the Mancos Shale unconformably overlies both the Gallup Sandstone and the nonmarine deposits of the Dilco Coal Member (figs. 5 and 14) (Molenaar, 1973, 1974, 1983).

Stone (1981, p. 6) reported that sandstone bodies in the Gallup Sandstone generally are pink to light gray, fine to medium grained, and are moderately to well sorted. The thickness of the Gallup is variable and decreases from about 300 feet near the outcrops along the southwestern margin of the basin until it is cut off to the northeast by the northwest-trending truncation line (Molenaar, 1974, fig. 2). The thickness also generally decreases southeastward from the Nutria Monocline to the Arroyo Chico-Rio Puerco area (Craigg, 1980, p. 59; Stone and others, 1983, fig. 58). The thickness of individual sandstone bodies (as defined by Molenaar, 1973, 1974, and 1983) ranges from a pinch-out edge to a maximum of about 150 feet (Stone, 1981, p. 7).

The depth to the top of the Gallup Sandstone ranges from outcrops to about 4,500 feet below the land surface in the truncated area about 20 miles south of Farmington, N. Mex. (fig. 15). The rapid increase in depth in the area northeast of Grants reflects the local topography of Mount Taylor.

The altitude and configuration of the top of the Gallup Sandstone are shown in figure 16. The altitude decreases from a maximum of about 7,500 feet above sea level along the outcrops in the western and southern parts of the basin, to about 1,500 feet above sea level in the subsurface near where the formation is truncated southwest of Farmington.

The Gallup Sandstone is a productive aquifer in the study area and is the major source of water for the town of Gallup (Cooley and Weist, 1979, p. 51; Stone and others, 1983, p. 36, 37; Kernodle and others, 1989). In the southeastern part of the basin, the U.S. Bureau of Land Management has constructed almost 200 miles of pipeline for a livestock-water distribution system that distributes water from a single, flowing artesian well completed in the Gallup Sandstone (Craigg, 1980, p. 62).

CREVASSE CANYON FORMATION

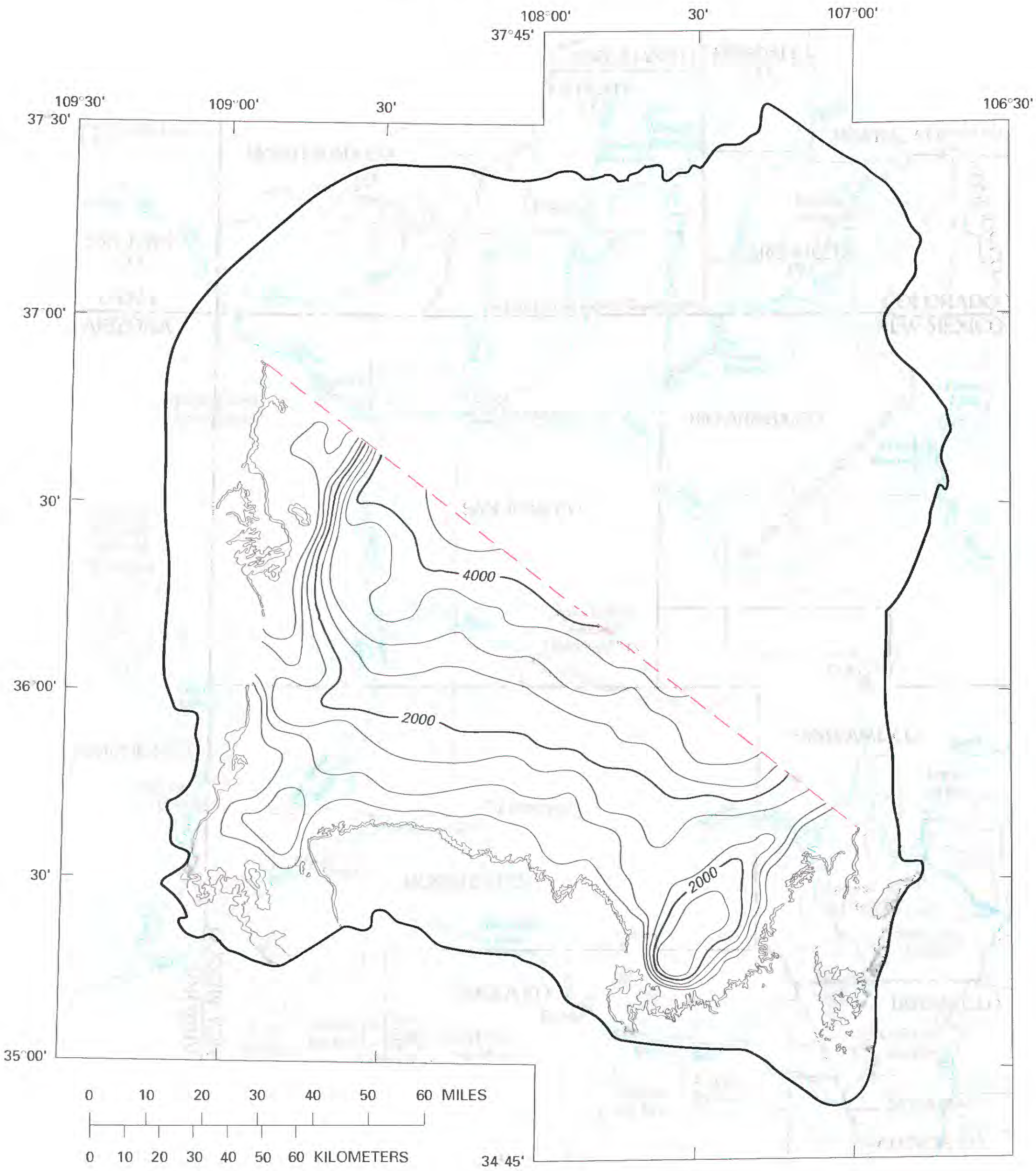
Allen and Balk (1954, p. 91–93) defined the Crevasse Canyon Formation for predominantly nonmarine sedimentary rocks between the top of the Gallup Sandstone and the bottom of the Hosta Tongue of the Point Lookout Sandstone. The stratotype is along the southern end of the Chuska Mountains in McKinley County, N. Mex.

The Crevasse Canyon Formation is present only in New Mexico and a small part of Arizona, in the south-southwestern part of the San Juan Basin (pl. 1). From its outcrops, the Crevasse Canyon dips northeast toward a northwest-trending truncation zone (similar to but not as far north as the truncation line of the Gallup Sandstone) that extends from the southeastern part of the basin, through the Chaco Culture National Historical Park area, to the area near Crystal in the Chuska Mountains. The Crevasse Canyon is not present northeast of this truncation zone; the upper part of the formation wedges against the Mancos Shale, and the lower part is truncated by a pre-Niobrara erosion surface (Molenaar, 1974, p. 252, figs. 2 and 3).

The Crevasse Canyon Formation conformably to disconformably overlies the Gallup Sandstone and is disconformably overlain by the Hosta Tongue of the Point Lookout Sandstone. In the Gallup Sag area, the Menefee Formation gradationally overlies the Crevasse Canyon (Molenaar, 1977b, p. 163, fig. 1). As defined by Allen and Balk (1954, p. 91–93), the Crevasse Canyon consists of (in ascending order) the Dilco Coal, Dalton Sandstone, and Gibson Coal Members. Beaumont and others (1956, p. 2153) recognized a fourth member, the Bartlett Barren Member. This member, however, is only of local significance and merges with the Gibson Coal (Molenaar, 1977b, p. 163). Correa (1970) named a fifth member as the Borrego Pass Sandstone Lentil, which is the same unit as the informal Stray sandstone of Sears and others (1941).

The Dilco Coal Member (fig. 5) consists of interbedded gray shale and claystone, carbonaceous shale, coal, yellowish-gray to pale-orange siltstone, and lenticular channel sandstone (Hackman and Olson, 1977; Stone, 1979). It forms ledges and slopes, and outcrop areas tend to have a badlands appearance. The Dilco Coal Member was deposited in continental environments (stream channels, flood plains, and swamps). The thickness ranges from zero along a wedge-edge in the subsurface between Crystal and the Chaco Culture National Historical Park in the southeastern basin to a maximum of about 300 feet in the Gallup area (Molenaar, 1974, figs. 2–4; Hackman and Olson, 1977).

The Dalton Sandstone Member (fig. 5) is a regressive marine shore-zone deposit (Molenaar, 1977b, p. 163). It mainly consists of cliff-forming, grayish-orange to grayish-yellow, very fine to medium-grained quartzose sandstone with some coarse-grained or conglomeratic sandstone (Hackman and Olson, 1977; Molenaar, 1977b, p. 163). The maximum thickness of the Dalton Sandstone Member is about 150 feet. It extends eastward to the Mesa Chivato area, where it maintains a uniform thickness of about 100 feet (Sears and others, 1941, p. 113). The Dalton Sandstone Member merges laterally into nonmarine, undivided Crevasse Canyon Formation deposits along a broad zone from about 5 miles northeast of Gallup to about 7 miles northeast of Window Rock, Ariz. (Hackman and Olson, 1977). The member pinches out into the Mancos Shale and merges with the Hosta Tongue of the Point Lookout Sandstone in the subsurface about halfway between Crownpoint and the Chaco



EXPLANATION

Outcrops of Gallup Sandstone—In Arizona, contains Pescado Tongue of the Mancos Shale. From Dane and Bachman (1965) and Hackman and Olson (1977)

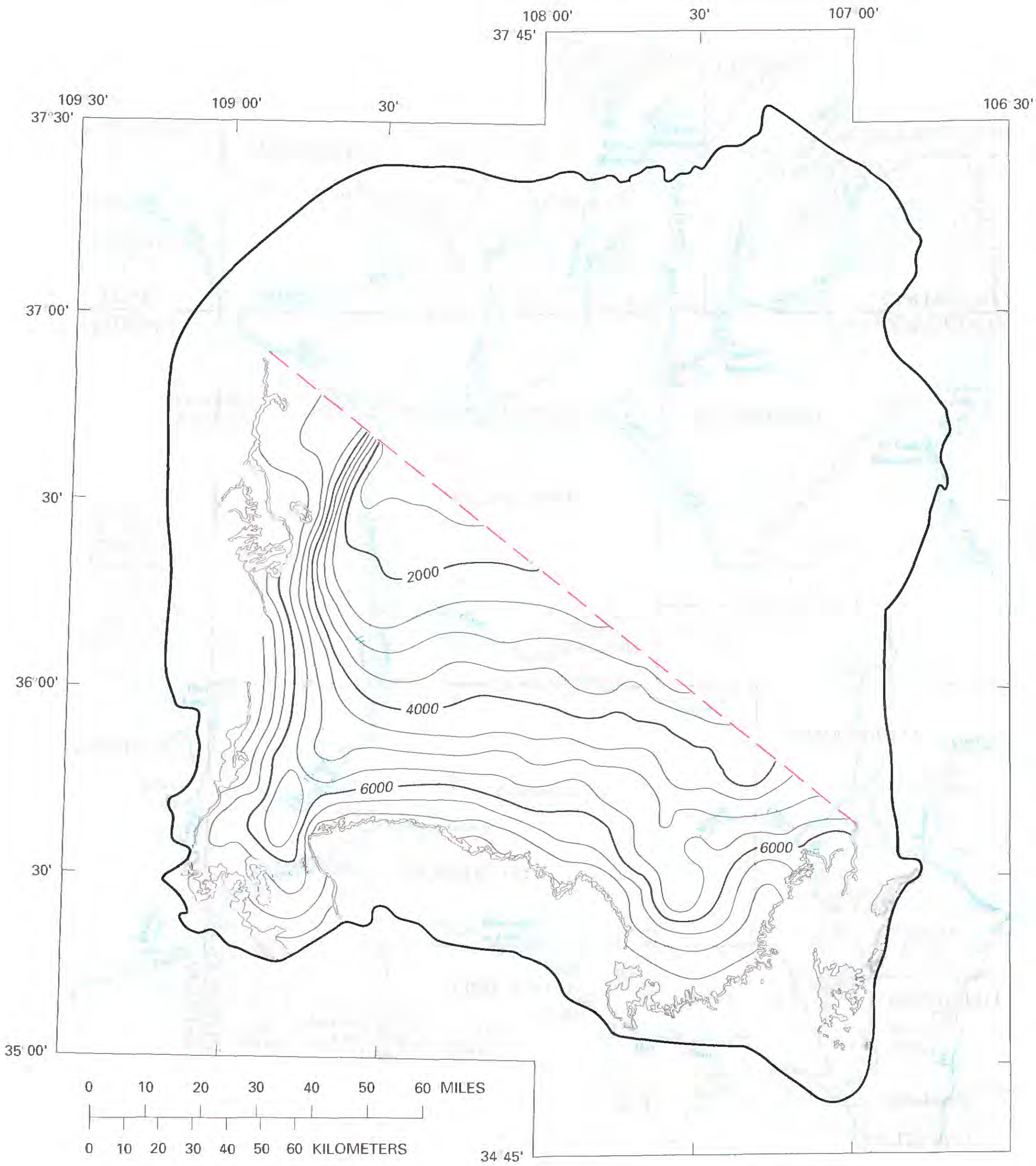
Outcrops of Mesaverde group, undivided—Contains Gallup Sandstone. From Dane and Bachman (1965)

Approximate subsurface extent of Gallup Sandstone—From Molenaar (1973)

Boundary of study area

2000 **Line of equal depth to top of Gallup Sandstone**—Interval 500 feet. Datum is land surface

FIGURE 15.—Approximate depth to the top of the Gallup Sandstone in the San Juan Basin study area. Modified from Kernodle and others (1989).



EXPLANATION

Outcrops of Gallup Sandstone—In Arizona, contains Pescado Tongue of the Mancos Shale. From Dane and Bachman (1965) and Hackman and Olson (1977)

Outcrops of Mesaverde group, undivided—Contains Gallup Sandstone. From Dane and Bachman (1965)

Approximate subsurface extent of Gallup Sandstone—From Molenaar (1973)

Boundary of study area

—*2000*— **Structure contour**—Shows altitude of top of Gallup Sandstone. Contour interval 500 feet. Datum is sea level

FIGURE 16.—Approximate altitude and configuration of the top of the Gallup Sandstone in the San Juan Basin study area. Modified from Kernodle and others (1989).

Culture National Historical Park area (Kirk and others, 1988).

The Gibson Coal Member is the uppermost member of the Crevasse Canyon Formation. South of the pinch out of the Hosta Tongue of the Point Lookout Sandstone, the Gibson Coal Member is gradationally overlain by the Cleary Coal Member of the Menefee Formation (fig. 5) (Molenaar, 1977b, p. 163). The Gibson Coal Member consists of the same types of continental deposits as those described for the Dilco Coal Member. The thickness of the Gibson Coal Member ranges from zero along a wedge-edge in the subsurface where the Dalton Sandstone Member and Hosta Tongue merge, to about 550 feet (Allen and Balk, 1954, p. 93).

Although the Dalton Sandstone Member probably is the most important aquifer in the Crevasse Canyon Formation, lenticular channel sandstone in the other members also yields water to wells locally. The lower part of the formation is hydraulically connected with the underlying Gallup Sandstone (Cooley and Weist, 1979, p. 50; Lyford, 1979, p. 12).

The Borrego Pass Lentil (Correa, 1970; Robertson, 1990), which replaces the informal Stray sandstone of Sears and others (1941), is situated between the Mulatto Tongue of the Mancos Shale and the Dilco Coal Member of the Crevasse Canyon Formation (fig. 5). Molenaar (1974, p. 256) stated that the Borrego Pass Lentil actually is a transgressive onlap deposit (a Tocito Sandstone Lentil of the Gallup Sandstone) associated with the pre-Niobrara unconformity. The lentil extends as a tongue-shaped wedge northwestward from the Mount Taylor area to the Crownpoint area (Sears and others, 1941, pl. 26). The lentil consists of cliff-forming, gray, fine- to coarse-grained, locally conglomeratic, crossbedded sandstone (Hackman and Olson, 1977). The thickness increases from zero along a wedge-edge near Crownpoint, to about 75 feet north of Thoreau, to about 100 feet near Grants (Sears and others, 1941, pl. 26). The small areal extent of this lentil makes it regionally insignificant as an aquifer, although locally it probably is capable of yielding small quantities of water to wells.

POINT LOOKOUT SANDSTONE

The Point Lookout Sandstone crops out beyond the margins of the Central Basin (pl. 1). The outcrops typically form cliffs, cap mesas and buttes, or form erosion-resistant dip slopes and hogbacks (as along the base of the Hogback Monocline).

The Point Lookout Sandstone, named by Collier (1919) for exposures at Mesa Verde National Park in southwestern Colorado, is the lowermost formation of the Mesaverde Group, which consists of the Point Lookout Sandstone, Menefee Formation, and Cliff House Sandstone in the San Juan Basin. The Point Lookout is the most extensive regressive marine beach sandstone in the basin (Molenaar, 1977b, p. 164). It conformably overlies the Mancos Shale throughout the basin (fig. 5); the contact is characterized by a distinct offshore marine transition zone consisting of interbedded thin sandstone, siltstone, and shale (Shetiwy, 1978; Craigg, 1980; Wright, 1984). The Menefee Formation conformably or disconformably overlies the Point Lookout Sandstone, with some local intertonguing at the contact (Tabet and Frost, 1979).

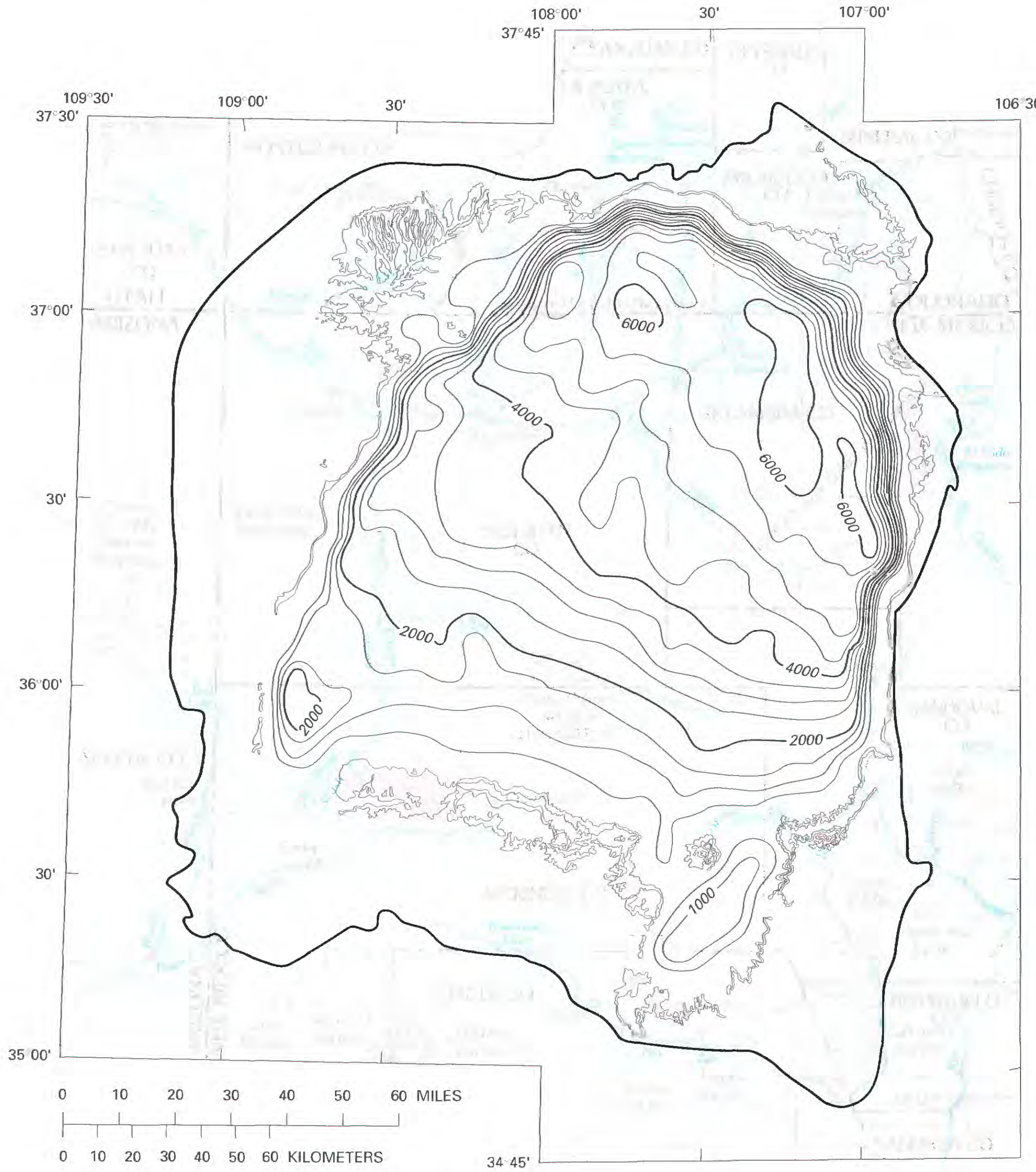
In the southern part of the San Juan Basin, the Point Lookout Sandstone is separated into two parts by the Satan Tongue of the Mancos Shale (fig. 5). The upper unit is the main body of the Point Lookout. The lower unit is the Hosta Tongue, which crops out between Crownpoint and the Arroyo Chico-Rio Puerco area in New Mexico (pl. 1). The Hosta Tongue is a transgressive marine beach sandstone. The main body of the Point Lookout and the Hosta Tongue merge along the southern margin of the basin, where they are about 250 feet thick (Sears and others, 1941; Beaumont and others, 1956, p. 2154). The Hosta Tongue is of limited areal extent, pinching out about 30 miles northeast of its outcrop (Beaumont, 1971, p. 22; Craigg, 1980). The tongue attains a maximum thickness of about 160 feet (Beaumont and others, 1956, p. 2155).

The Point Lookout Sandstone generally consists of light-gray, thick- to very thick bedded, very fine to medium-grained, locally crossbedded sandstone (Shetiwy, 1978; Craigg, 1980; Wright, 1984). Thin interbeds of dark marine shale also are present, especially in the lower part of the formation. The Point Lookout yields small quantities of water to wells, especially in the Mesa Chivato area of the southeastern San Juan Basin (Cooley and Weist, 1979, p. 49; Craigg, 1980, p. 48–52; Craigg and others, 1990).

The thickness of the Point Lookout Sandstone is variable. Beaumont (1971, p. 22) reported the formation as varying irregularly from about 100 feet in the southern part of the basin to about 350 feet near the Colorado-New Mexico State line. Molenaar (1977a) reported a maximum thickness of 300 feet. Stone and others (1983, p. 34) reported a thickness range from 40 to 415 feet in New Mexico.

The depth to the top of the Point Lookout Sandstone ranges from outcrops to between 6,000 and 6,500 feet in the northeastern part of the study area (fig. 17). The increase in depth in the area northeast of Grants reflects the local topography of Mount Taylor; the increase in depth in the area northeast of Window Rock reflects the synclinal structure of the Gallup Sag.

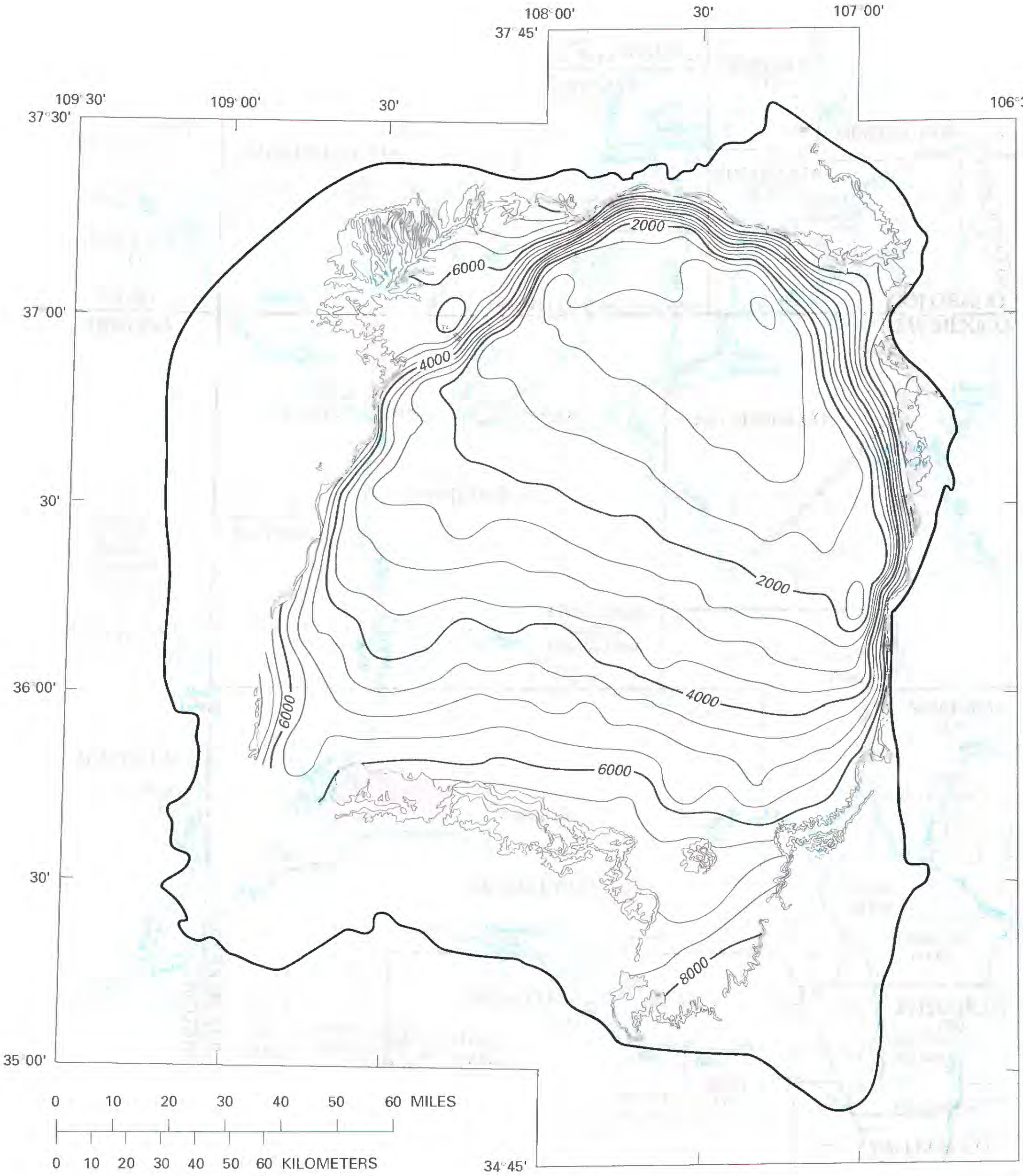
The altitude and configuration of the top of the Point Lookout Sandstone are shown in figure 18. The top of the Point Lookout decreases from a maximum altitude of about 8,000 feet above sea level on the outcrops along the north-central and southeastern basin margins, to about 500 feet above sea level in the subsurface in the northeastern part of the study area.



EXPLANATION

- **Outcrops of Point Lookout Sandstone**—From Dane and Bachman (1965)
- **Outcrops of Hosta Tongue of Point Lookout Sandstone**—From Dane and Bachman (1965)
- **Outcrops of Menefee Formation and Point Lookout Sandstone**—From Tweto (1979)
- **Outcrops of Mesaverde Group, undivided**—Contains Point Lookout Sandstone. From Dane and Bachman (1965) and Tweto (1979)
- **Boundary of study area**
- *2000* **Line of equal depth to top of Point Lookout Sandstone**—Interval 500 feet. Datum is land surface

FIGURE 17.—Approximate depth to the top of the Point Lookout Sandstone in the San Juan basin study area. Modified from Craigg and others (1990).



EXPLANATION

Outcrops of Point Lookout Sandstone—From Dane and Bachman (1965)

Outcrops of Hosta Tongue of Point Lookout Sandstone—From Dane and Bachman (1965)

Outcrops of Menefee Formation and Point Lookout Sandstone—From Tweto (1979)

Outcrops of Mesaverde Group, undivided—Contains Point Lookout Sandstone. From Dane and Bachman (1965) and Tweto (1979)

Boundary of study area

—*2000*— **Structure contour**—Shows altitude of top of Point Lookout Sandstone. Contour interval 500 feet. Datum is sea level

FIGURE 18.—Approximate altitude and configuration of the top of the Point Lookout Sandstone in the San Juan Basin study area. Modified from Craigg and others (1990).

MENEFEE FORMATION

The Menefee Formation (fig. 5) crops out beyond the margins of the Central Basin (pl. 1). Erosion-resistant sandstone in the Menefee commonly caps isolated buttes and hillocks, whereas less resistant shale units form slopes and broad valleys or flats. The topography on Menefee outcrops typically is rolling to rough, broken and steep, and generally has a badlands appearance. The upper part of the Menefee commonly forms steep slopes below mesas or buttes capped by the erosion-resistant Cliff House Sandstone.

The Menefee Formation, named by Collier (1919) for exposures near Mesa Verde National Park in southwestern Colorado, is the middle formation of the Mesaverde Group in the San Juan Basin. The Menefee conformably or disconformably overlies the Point Lookout Sandstone and is conformably or disconformably overlain by the Cliff House Sandstone; local intertonguing occurs at both contacts (Tabet and Frost, 1979; Craigg, 1980; Stone and others, 1983). Some authors have reported the Menefee to be conformably overlain by the Lewis Shale in the southeastern part of the basin (Dane, 1936; Beaumont and others, 1956). South of the pinch out of the Point Lookout in the vicinity of Gallup, the Menefee conformably and gradationally overlies the Crevasse Canyon Formation.

The Menefee Formation generally consists of interbedded and repetitive sequences of variously thick sandstone, siltstone, shale, claystone, carbonaceous shale, and coal beds (Collier, 1919; Sears and others, 1936; Mannhard, 1976; Tabet and Frost, 1979; Craigg, 1980). Typically, the (1976) stone is lenticular, light brown to gray, thick to very thick bedded, and fine to medium grained, with a clay matrix and various types of cement (calcium carbonate, iron oxide, silica). The siltstone commonly is tabular, gray, and thin to thick bedded; the shale and claystone typically are light-brownish gray and thick to very thick bedded (Mannhard, 1976; Tabet and Frost, 1979; Craigg, 1980). Although the Menefee acts as a regional confining unit, the lenticular channel sandstone beds yield dependable quantities of water to stock wells throughout the formation's extent (Cooley and Weist, 1979, p. 48; Lyford, 1979, p. 12; Craigg, 1980, p. 39, 40; Stone and others, 1983, p. 34; Levings and others, 1990a).

The Menefee Formation usually is mapped as an undivided formation; however, in the southern part of the basin, two formal members and one informal member can easily be differentiated (Tabet and Frost, 1979; Craigg, 1980). In ascending order, these are the Cleary Coal Member, consisting of abundant carbonaceous shale and coal beds, gray shale and claystone, siltstone, and scattered channel sandstone; the Allison Member, mainly a thick sequence of stacked channel sandstone with some siltstone, gray shale, and claystone; and the upper coal-bearing member, which is similar to the Cleary Coal Member and includes the Hogback Mountain tongue of Shomaker and Whyte (1977).

The thickness of the Menefee Formation increases from north to south. It ranges from zero where the unit pinches out between the Point Lookout and Cliff House Sandstones in Colorado, to about 2,000 feet in the Chaco Culture p. 164; National Historical Park-Torreon areas (Molenaar, 1977b, Tabet and Frost, 1979). The depth to the top of the Menefee ranges from outcrops to between 6,000 and 6,500 feet in the northeastern part of the study area (fig. 19). The altitude and configuration of the top of the Menefee are shown in figure 20. The top surface decreases from a maximum altitude of about 8,000 feet above sea level on the outcrops along the north-central basin margin near Durango to about 1,000 feet above sea level in the subsurface beneath Navajo Reservoir in the northeastern part of the study area.

CLIFF HOUSE SANDSTONE

Cliff House Sandstone outcrops form the margins of the Central Basin (pl. 1). Typically, the Cliff House caps mesas (as in the Chaco Culture National Historical Park area and southwest of Cuba) and forms erosion-resistant dip slopes and hogbacks (as on the Hogback Monocline). The Cliff House Sandstone, named by Collier (1919) for exposures at Mesa Verde National Park in southwestern Colorado, is the uppermost formation of the Mesaverde Group in the San Juan Basin.

The Cliff House Sandstone is conformably overlain by and intertongues with the Lewis Shale and in turn conformably and unconformably overlies the Menefee Formation, with which it locally intertongues (Molenaar, 1977b, p. 164; Craigg, 1980, p. 7). In some areas where Cliff House tongues pinch out, the Lewis may directly overlie the Menefee (Stone and others, 1983, p. 33). In the western part of the basin near the confluence of Coyote Wash and the Chaco River, the Cliff House merges with the Pictured Cliffs Sandstone, pinching out the Lewis (fig. 5). Cliff House strata consist of several sandstone tongues that represent marine shore-zone deposits of an overall transgressing shallow sea. Molenaar (1977b, p. 164) noted that these sandstone tongues actually are offlap, or regressive, deposits formed during stillstands and minor regressions of the shoreline.

The stratigraphy of the Cliff House Sandstone is complex. Continuing nomenclature controversies, differing geologic interpretations, and informal oil-field terminology tend to further complicate stratigraphic correlations. The geometry of the Cliff House is much different from that of the Point Lookout and Pictured Cliffs Sandstones (Fassett, 1977, p. 193). The stratigraphic sequence of the Cliff House consists of several sandstone tongues of varying thicknesses and areal extents. Some of these sandstone tongues have been formally named, whereas informal nomenclature is applied to others.

Fassett (1977), who gave an excellent, consise summary of the Cliff House Sandstone, reported that the sequence

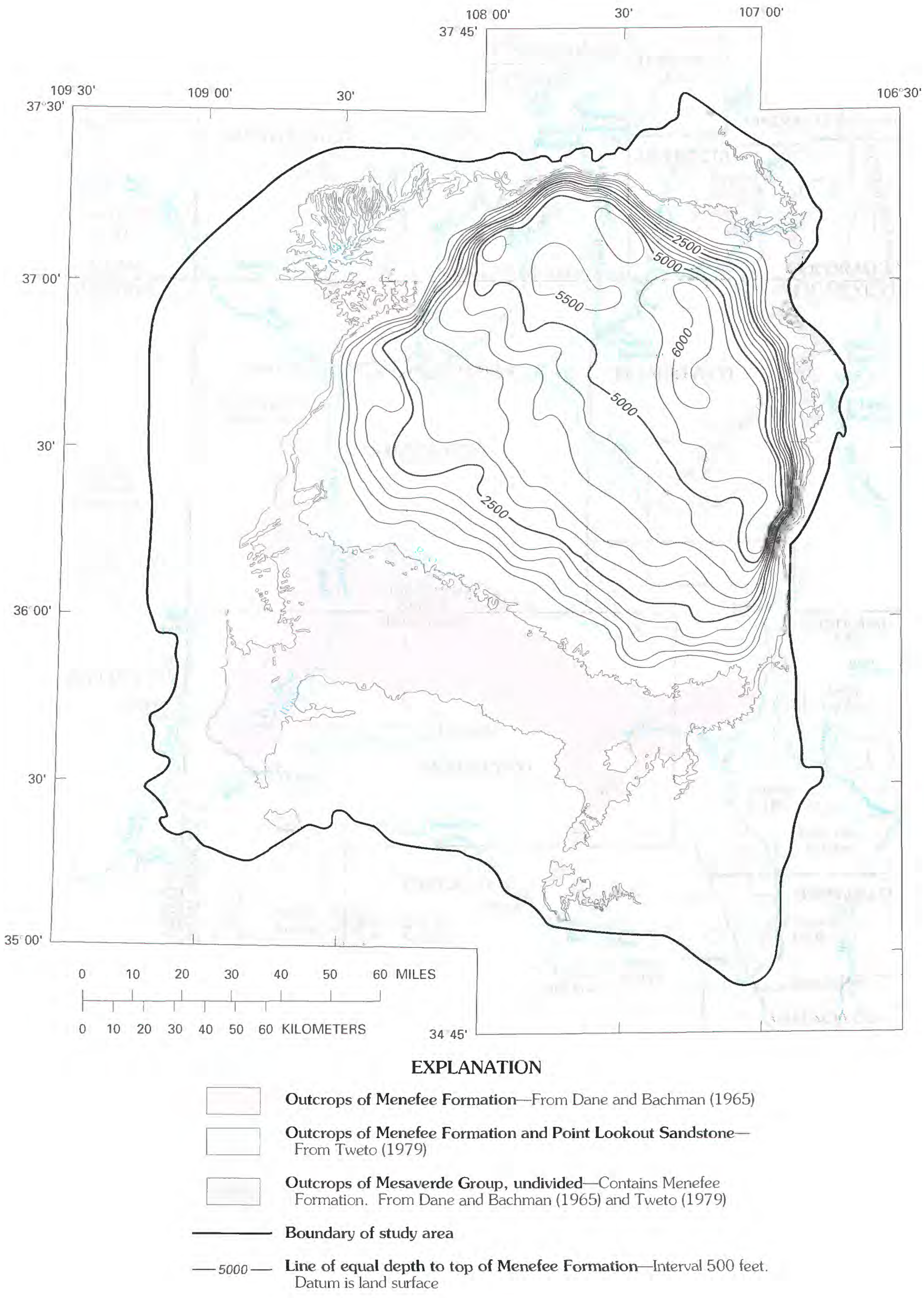
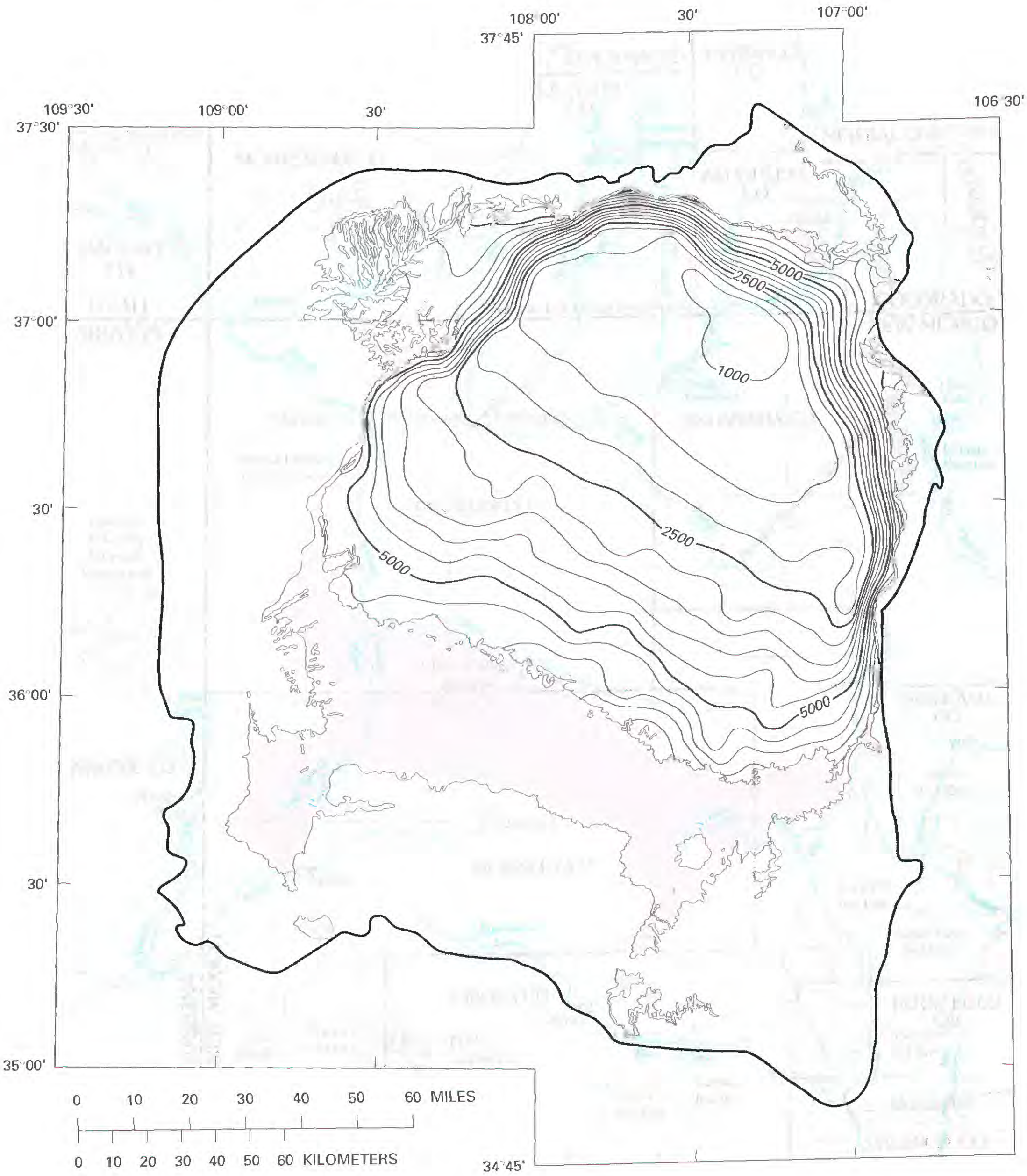


FIGURE 19.—Approximate depth to the top of the Menefee Formation in the San Juan Basin study area. Modified from Levings and others (1990a).



EXPLANATION

Outcrops of Menefee Formation—From Dane and Bachman (1965)

Outcrops of Menefee Formation and Point Lookout Sandstone—From Tweto (1979)

Outcrops of Mesaverde Group, undivided—Contains Menefee Formation. From Dane and Bachman (1965) and Tweto (1979)

Boundary of study area

5000 **Structure contour**—Shows altitude of top of Menefee Formation. Contour interval 500 feet. Datum is sea level

FIGURE 20.—Approximate altitude and configuration of the top of the Menefee Formation in the San Juan Basin study area. Modified from Levings and others (1990a).

consists of a few sandstone lenses at the base (the "basal" Cliff House Sandstone), the thick La Ventana Tongue in the middle, and a major, unnamed tongue at the top. The stratigraphic relations of these tongues with one another and with adjacent formations are shown diagrammatically in figure 5.

The basal Cliff House Sandstone tongues are common in the deeper part of the Central Basin but are of limited thickness (aggregate thickness of about 300 feet); these basal tongues also are of limited areal extent and pinch out to the northeast (Molenaar, 1977b, p. 164; Stone and others, 1983, sheets 2–4). Some of these tongues actually have been named, but the names are not commonly used. For example, the Barker Dome Tongue was named by Wanek (1954), and the Cholla Canyon Tongue and Beechatuda Tongue were named by Hayes and Zapp (1955)

South of Cuba, in the southeastern part of the basin, the thick sandstone sequence named La Ventana Tongue of the Cliff House Sandstone crops out (pl. 1). According to authors most familiar with the regional stratigraphy of the San Juan Basin (Fassett, 1977; Molenaar, 1977b, p. 164), La Ventana Tongue can be traced from its outcrops in the southeast, through the subsurface across the basin, to outcrops on the Hogback Monocline a few miles west of Farmington. Other authors (Mannhard, 1976; Fuchs-Parker, 1977) have reported that La Ventana Tongue is a more localized sandstone sequence that is present only in the southeastern part of the basin and represents deposition in a deltaic environment rather than in a marine shore-zone environment. Mannhard (1976) and Tabet and Frost (1979) showed the tongue pinching out 15–20 miles west of the village of La Ventana.

La Ventana Tongue unconformably to conformably overlies the Menefee Formation, and intertonguing is common; the Lewis Shale conformably overlies La Ventana Tongue, and intertonguing also is common. The maximum thickness of La Ventana Tongue according to Molenaar (1977b, p. 164) is about 800 feet. Mannhard (1976, p. 39) and Fuchs-Parker (1977, p. 199), however, reported a maximum thickness of about 1,000 feet in outcrops along State Highway 44 south of Cuba.

The upper, unnamed tongue of the Cliff House Sandstone represents the stratotype at Mesa Verde National Park and also forms the prominent outcrop belt that bounds the southern part of the Central Basin in the vicinity of the Chaco Culture National Historical Park. This tongue formerly was called the Chacra Sandstone Member of the Mesaverde Formation (Fassett, 1977, p. 196). To avoid confusion with informal oil-field terminology, Fassett (1977, p. 197) has suggested the term Tsaya Canyon Tongue for this interval. The thickness of the tongue is about 400 feet at the stratotype (Collier, 1919, p. 297). Molenaar (1977b, p. 164) reported a range in thickness of 150–300 feet, whereas Stone and others (1983, p. 33) reported that the thickness of this tongue throughout most of its extent in New Mexico ranges from zero to about 250 feet. The upper, unnamed tongue intertongues with both the underlying Menefee Formation and the overlying Lewis Shale.

The Cliff House Sandstone generally consists of tan, light-brown, or yellowish-brown, thick to very thick bedded and locally crossbedded sandstone with calcite or silica cement and clay matrix. Grain size ranges from very fine to fine and the sandstone is well to very well sorted (Stone and others, 1983, p. 28, 33). Interbeds of gray shale and silty shale are common (O'Sullivan and Beikman, 1963; Haynes and others, 1972; Craigg, 1980). Cooley and Weist (1979, p. 47) reported that the Cliff House generally is a dependable, small-yielding aquifer. Thorn and others (1990a) reported on the hydrogeology of the formation.

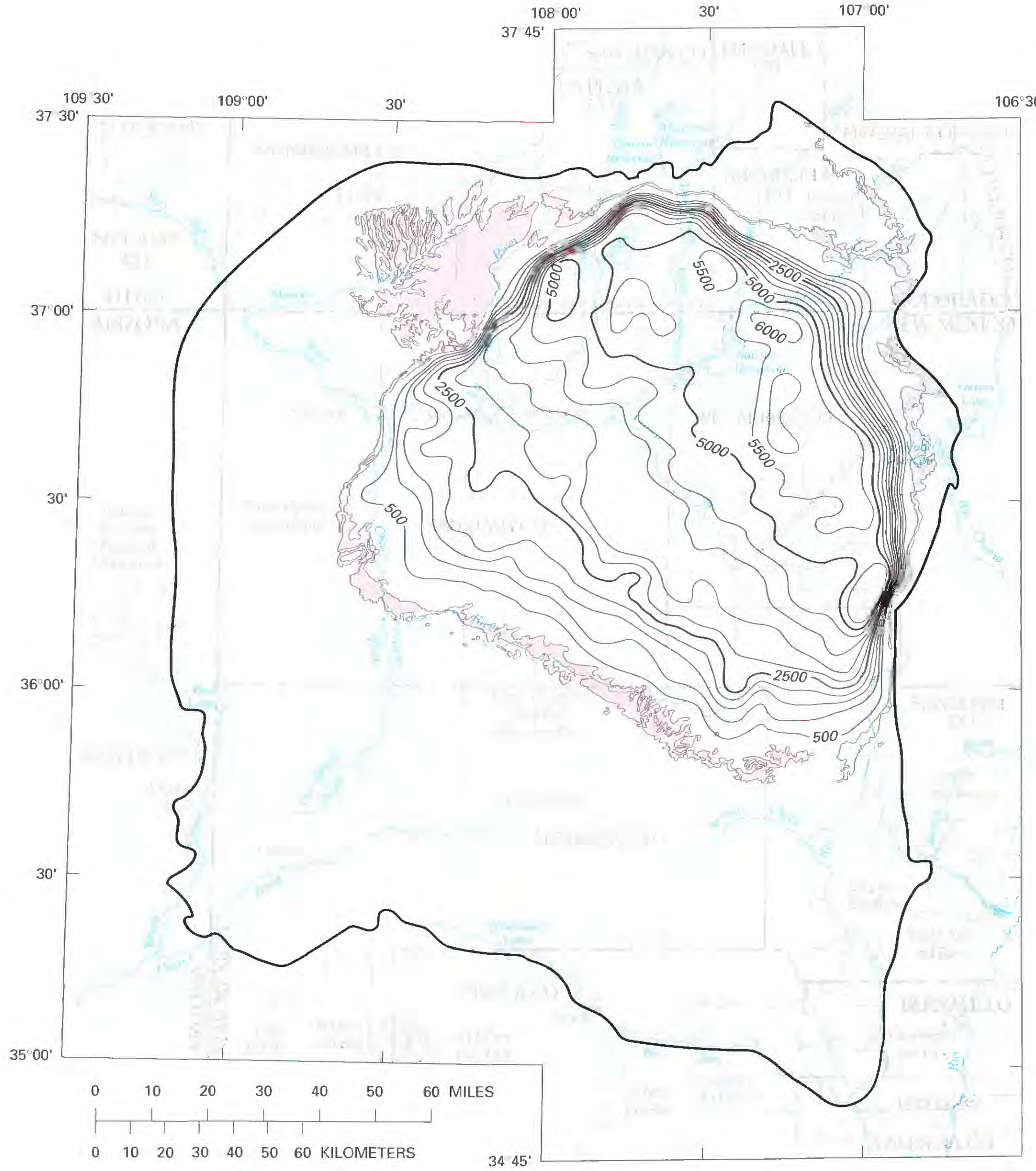
The depth to the top of the Cliff House Sandstone ranges from outcrops to about 6,000 feet in the northeastern part of the study area (fig. 21). The altitude and configuration of the top of the Cliff House is shown in figure 22. The top of the formation decreases from a maximum altitude of about 8,500 feet above sea level on the outcrops along the northeastern and northern rims of the Central Basin, to about 1,000 feet above sea level in the subsurface beneath Navajo Reservoir, near the structural center of the basin.

LEWIS SHALE

The Lewis Shale crops out inside the margins of the Central Basin (pl. 1). The topography formed on the formation outcrops is rolling to flat, rough and broken, and generally has a badlands appearance. Localized erosion-resistant siltstone and sandstone cap isolated buttes and hillocks, whereas less resistant shale forms slopes and broad valleys or flats. The upper part of the Lewis commonly forms steep slopes below mesas or buttes capped by the Pictured Cliffs Sandstone.

The Lewis Shale was named by Cross and others (1899) for exposures in the La Plata River valley, about 15 miles southwest of Durango. The Lewis conformably overlies and intertongues with the Cliff House Sandstone (fig. 5). This intertonguing is especially evident in the southeastern part of the basin, where several fingers of La Ventana Tongue of the Cliff House Sandstone are present in the lower part of the Lewis (Mannhard, 1976, p. 76; Molenaar, 1977b, p. 164). Locally, the Lewis conformably overlies the Menefee Formation (Shomaker, 1971b, p. 94; Stone and others, 1983, p. 33) and is in turn conformably overlain by the Pictured Cliffs Sandstone; the latter contact is characterized by a distinct offshore marine transition zone consisting of interbedded thin shale, siltstone, and sandstone (Reeside, 1924, p. 19; Fassett and Hinds, 1971, p. 8).

The Lewis Shale was deposited in an offshore marine environment. The strata represent the final major transgression of the Cretaceous sea in the San Juan Basin and, thus,



EXPLANATION

Outcrops of Cliff House Sandstone—From Dane and Bachman (1965) and Tweto (1979)

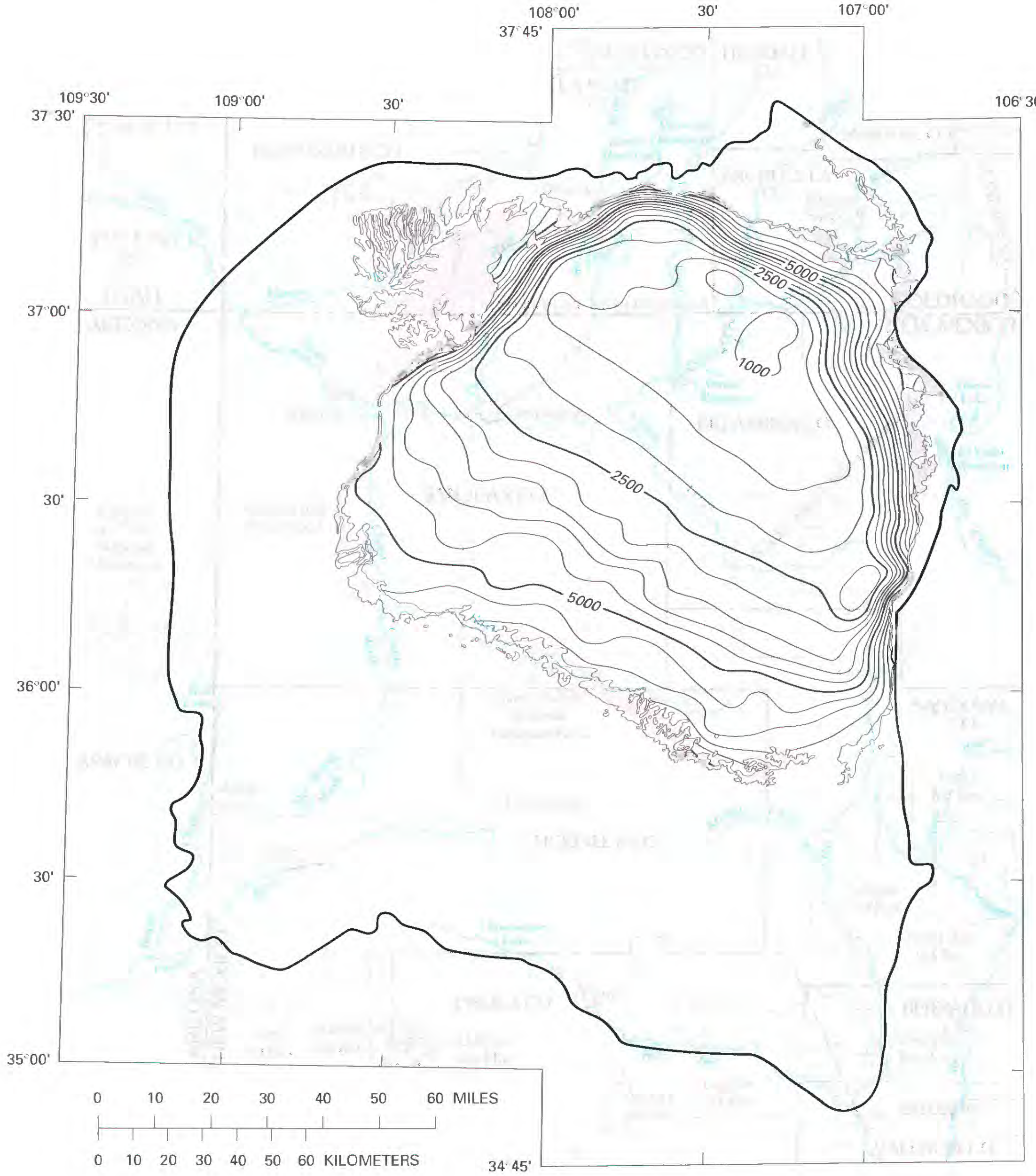
Outcrops of La Ventana Tongue of Cliff House Sandstone—From Dane and Bachman (1965)

Outcrops of Mesaverde Group, undivided—Contains Cliff House Sandstone. From Dane and Bachman (1965) and Tweto (1979)

Boundary of study area

—5000— **Line of equal depth to top of Cliff House Sandstone**—Interval 500 feet. Datum is land surface

FIGURE 21.—Approximate depth to the top of the Cliff House Sandstone in the San Juan Basin study area. Modified from Thorn and others (1990a).



EXPLANATION

Outcrops of Cliff House Sandstone—From Dane and Bachman (1965) and Tweto (1979)

Outcrops of La Ventana Tongue of Cliff House Sandstone—From Dane and Bachman (1965)

Outcrops of Mesaverde Group, undivided—Contains Cliff House Sandstone. From Dane and Bachman (1965) and Tweto (1979)

Boundary of study area

5000 **Structure contour**—Shows altitude of top of Cliff House Sandstone. Contour interval 500 feet. Datum is sea level

FIGURE 22.—Approximate altitude and configuration of the top of the Cliff House Sandstone in the San Juan Basin study area. Modified from Thorn and others (1990a).

the Lewis is stratigraphically the highest marine shale in the basin (Fassett and Hinds, 1971, p. 6). In general, the Lewis consists of light- to dark-gray and black shale and silty shale with thinner interbeds of silty to sandy limestone, siltstone, and fine-grained sandstone; calcareous concretions also are present in the unit (Baltz, 1967, p. 15, 16; Fassett and Hinds, 1971, p. 6). Baltz (1967, p. 15) reported that the sandstone interbeds are most common in the lower part of the formation. The Lewis also contains several bentonite time-marker beds. The thickest and most extensive of these, the Huerfanito Bentonite Bed named by Fassett and Hinds (1971, p. 6), is in the upper part of the Lewis and is used for regional subsurface correlations.

The thickness of the Lewis Shale increases from southwest to northeast (fig. 5). The thickness ranges from zero where the formation pinches out between the Cliff House and Pictured Cliffs Sandstones near the junction of the Chaco River and Coyote Wash in New Mexico (pl. 1), to a maximum of about 2,400 feet in the Colorado part of the San Juan Basin (Fassett and Hinds, 1971, p. 6). The depth to the top of the Lewis ranges from 4,000 to 4,500 feet below land surface.

The Lewis Shale generally acts as a confining unit between the Cliff House and Pictured Cliffs Sandstones (Cooley and Weist, 1979, p. 46). Water wells reportedly completed in this formation actually may be completed in various sandstone tongues of the underlying and intertonguing Cliff House Sandstone.

PICTURED CLIFFS SANDSTONE

The Pictured Cliffs Sandstone was named by Holmes (1877, p. 248) for exposures north of the San Juan River between Shiprock and Farmington. The Pictured Cliffs crops out inside the margins of the Central Basin (pl. 1), where the sandstone caps mesas and buttes or forms erosion-resistant dip slopes. The Pictured Cliffs typically is a cliff former, although along the southeastern outcrop belt, the unit is very thin and forms low, nonresistant slopes. There is some debate as to the presence of the Pictured Cliffs Sandstone along the eastern margin of the San Juan Basin. Baltz (1967, p. 17) considered the formation to be present in that area but stated that it is represented only by a thin, silty and shaly offshore marine transition zone that merges with the upper part of the Lewis Shale. Fassett and Hinds (1971, p. 16), however, stated that the Pictured Cliffs is not present along the eastern side of the basin and that the Lewis Shale is overlain unconformably by the undivided Fruitland Formation and Kirtland Shale.

The Pictured Cliffs Sandstone is a regressive marine beach deposit (Molenaar, 1977b, p. 165). The formation conformably overlies the Lewis Shale (fig. 5), with the contact characterized by a distinct offshore marine transition zone consisting of interbedded thin sandstone, siltstone, and shale (Reeside, 1924, p. 19; Fassett and Hinds, 1971, p. 8). The Upper Cretaceous Fruitland Formation conformably overlies the Pictured Cliffs, and intertonguing locally occurs between the two formations (Fassett and Hinds, 1971, p. 8).

The Pictured Cliffs Sandstone generally consists of an upward-coarsening sequence of light-gray to yellowish-gray, thick- to very thick bedded, very fine to medium-grained, locally crossbedded and bioturbated sandstone. Thin interbeds of dark marine shale also are present, especially in the lower part of the formation (Baltz, 1967, p. 17, 18; Fassett and Hinds, 1971, p. 8). The Pictured Cliffs is an aquifer throughout the Central Basin, but well yields are small (Cooley and Weist, 1979, p. 46; Stone and others, 1983, p. 32; Dam and others, 1990b).

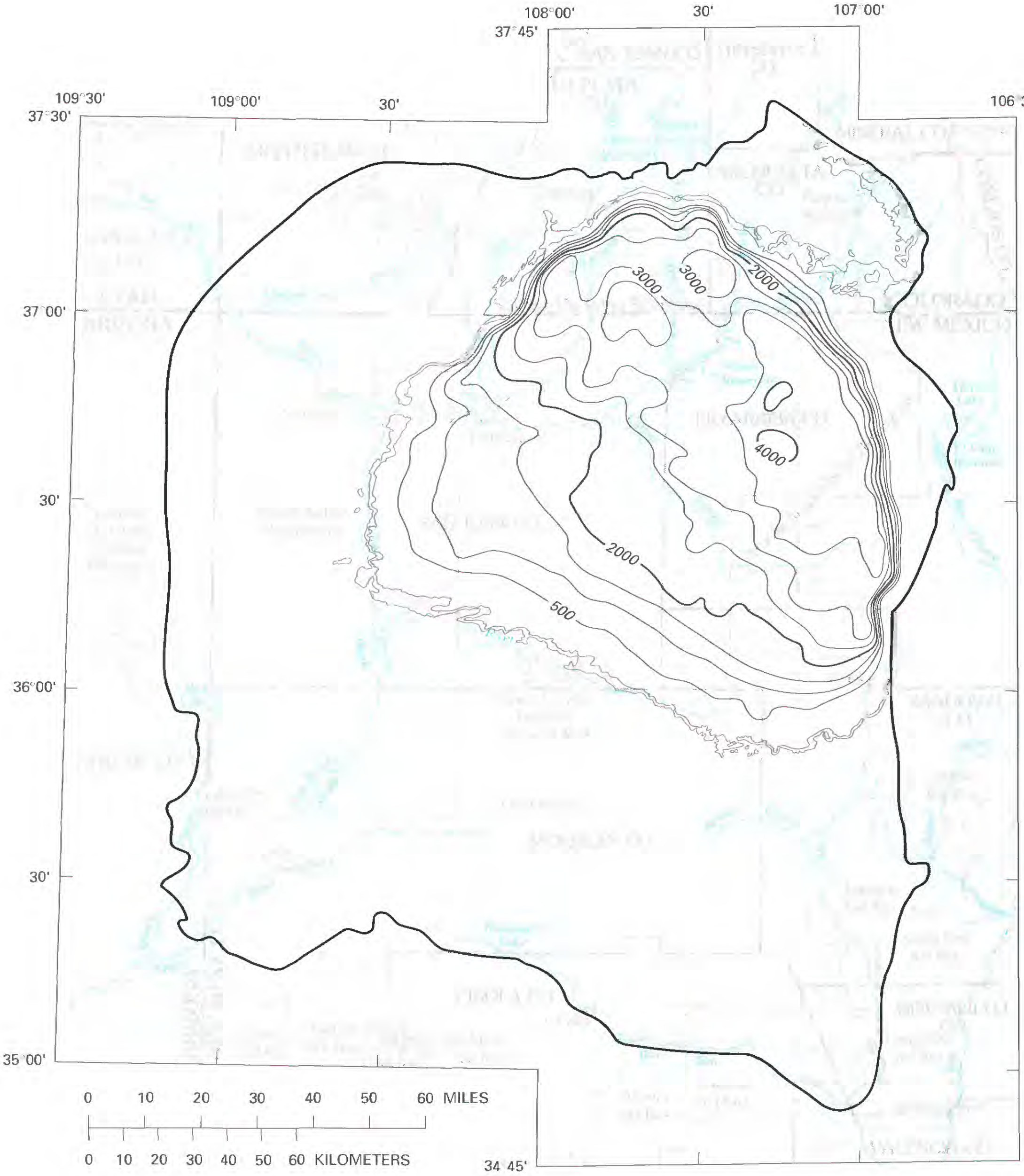
The thickness of the Pictured Cliffs Sandstone is variable. Molenaar (1977a) reported a maximum thickness of 400 feet but also reported that the average thickness is much less (Molenaar, 1977b, p. 165). Fassett and Hinds (1971, p. 17) stated that thickness ranges from zero on the east side of the basin to about 400 feet in the north-central part of the basin. Stone and others (1983, p. 33) reported a thickness range of 25–280 feet in New Mexico.

The depth to the top of the Pictured Cliffs Sandstone ranges from outcrops to about 4,000 feet in the northeastern part of the study area (fig. 23). The altitude and configuration of the top of the Pictured Cliffs is shown in figure 24. The top surface decreases from a maximum altitude of about 8,000 feet above sea level on the outcrops along the northern rim of the Central Basin, to about 3,000 feet above sea level in the northeastern part of the study area, beneath Navajo Reservoir.

FRUITLAND FORMATION AND KIRTLAND SHALE

The Fruitland Formation and Kirtland Shale crop out inside the margins of the Central Basin (pl. 1). The topography formed by their outcrops varies from rolling to rough and typically resembles badlands. Erosion-resistant sandstone commonly caps isolated buttes and hillocks, whereas less resistant shale forms slopes and broad valleys or flats. The upper part of the Kirtland Shale generally forms steep slopes below mesas or buttes capped by the overlying erosion-resistant Ojo Alamo Sandstone.

The Fruitland Formation and Kirtland Shale were named by Bauer (1916) for exposures near the villages of Fruitland and Kirtland, N. Mex., along the San Juan River west of Farmington. The Fruitland conformably overlies the Pictured Cliffs Sandstone, with local intertonguing at the contact, and is conformably overlain by the Kirtland Shale. The Kirtland is unconformably overlain by the Ojo Alamo Sandstone of Tertiary age (fig. 5) (Baltz, 1967; Fassett and Hinds, 1971; Molenaar, 1977b). In southwestern Colorado,



EXPLANATION

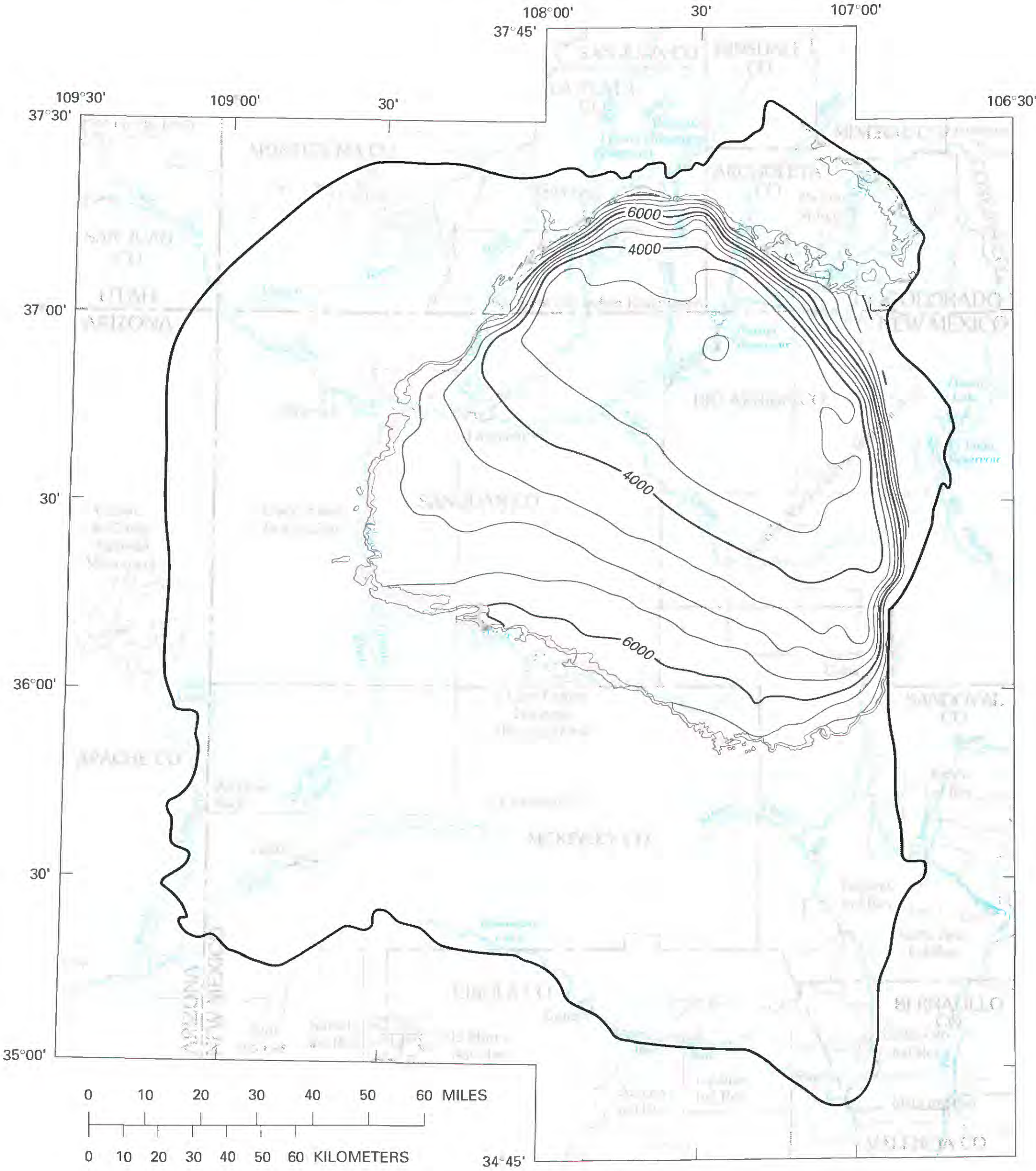
Outcrops of Pictured Cliffs Sandstone—From Dane and Bachman (1965)

Outcrops of Pictured Cliffs Sandstone and Lewis Shale, undivided—From Tweto (1979)

Boundary of study area

2000 **Line of equal depth to top of Pictured Cliffs Sandstone**—Interval 500 feet. Datum is land surface

FIGURE 23.—Approximate depth to the top of the Pictured Cliffs Sandstone in the San Juan Basin study area. Modified from Dam and others (1990b).



EXPLANATION

Outcrops of Pictured Cliffs Sandstone—From Dane and Bachman (1965)

Outcrops of Pictured Cliffs Sandstone and Lewis Shale, undivided—From Tweto (1979)

Boundary of study area

4000 **Structure contour**—Shows altitude of top of Pictured Cliffs Sandstone. Contour interval 500 feet. Datum is sea level

FIGURE 24.—Approximate altitude and configuration of the top of the Pictured Cliffs Sandstone in the San Juan Basin study area. Modified from Dam and others (1990b).

the upper part of the Kirtland is overlain by and intertongues with the Upper Cretaceous McDermott Member of the Animas Formation (fig. 5).

In general, the Fruitland Formation and Kirtland Shale both consist of variable thicknesses of interbedded and repetitive sequences of nonmarine channel sandstone, siltstone, shale, and claystone. Coal beds and carbonaceous shales are common in the Fruitland. The Kirtland does not contain coal and has been divided into the following three members (in ascending order): the lower shale member of informal usage, the Farmington Sandstone Member, and the upper shale member of informal usage (fig. 5) (Bauer, 1916). Regionally, the Fruitland and Kirtland together probably act as a confining unit; however, the formations yield water to wells locally (Baltz and West, 1967, p. 16, 17; Brown, 1976, p. 53, 54; Anderholm, 1979, p. 36, 37; Cooley and Weist, 1979, p. 45, 46).

The thickness of the combined Fruitland Formation and Kirtland Shale ranges from zero on the eastern side of the basin (because of the uncomformity at the base of the Ojo Alamo Sandstone) to a maximum of about 2,000 feet in the northwestern part of the basin (fig. 25) (Fassett and Hinds, 1971, p. 22, 26; Molenaar, 1977b, p. 165). The Fruitland ranges in thickness from zero along the eastern side to about 500 feet in the northwestern part of the basin (Fassett and Hinds, 1971, p. 23), with an average thickness of 300-350 feet (Molenaar, 1977b, p. 165). The thickness of the Kirtland ranges from zero along the eastern side to about 1,500 feet in the northwestern part of the basin; the lower shale member, Farmington Sandstone Member, and upper shale member of the Kirtland Shale each are as much as 500 feet thick (Fassett and Hinds, 1971, p. 26; Molenaar, 1977b, p. 165; Stone and others, 1983, p. 31).

The depth to the top of the Kirtland Shale ranges from outcrops to about 3,500 feet in the eastern part of the basin (fig. 26). The altitude and configuration of the top of the Kirtland is shown in figure 27. It decreases from a maximum altitude of about 8,000 feet above sea level on the outcrops along the northeast to about 3,500 feet above sea level in the subsurface in the eastern part of the study area.

TERTIARY ROCKS

Sedimentary rocks of early Tertiary age in the Central Basin consist of the Ojo Alamo Sandstone, upper part of the Animas Formation (the lower part of the Animas, the McDermott Member, is of Late Cretaceous age; however, to avoid repetition, both parts are discussed in this section), Nacimiento Formation, and San Jose Formation (fig. 5). In the western part of the basin, the Chuska Sandstone (not shown in fig. 5) caps the Chuska Mountains. Tertiary rocks in the Central Basin disconformably overlie Upper Cretaceous rocks.

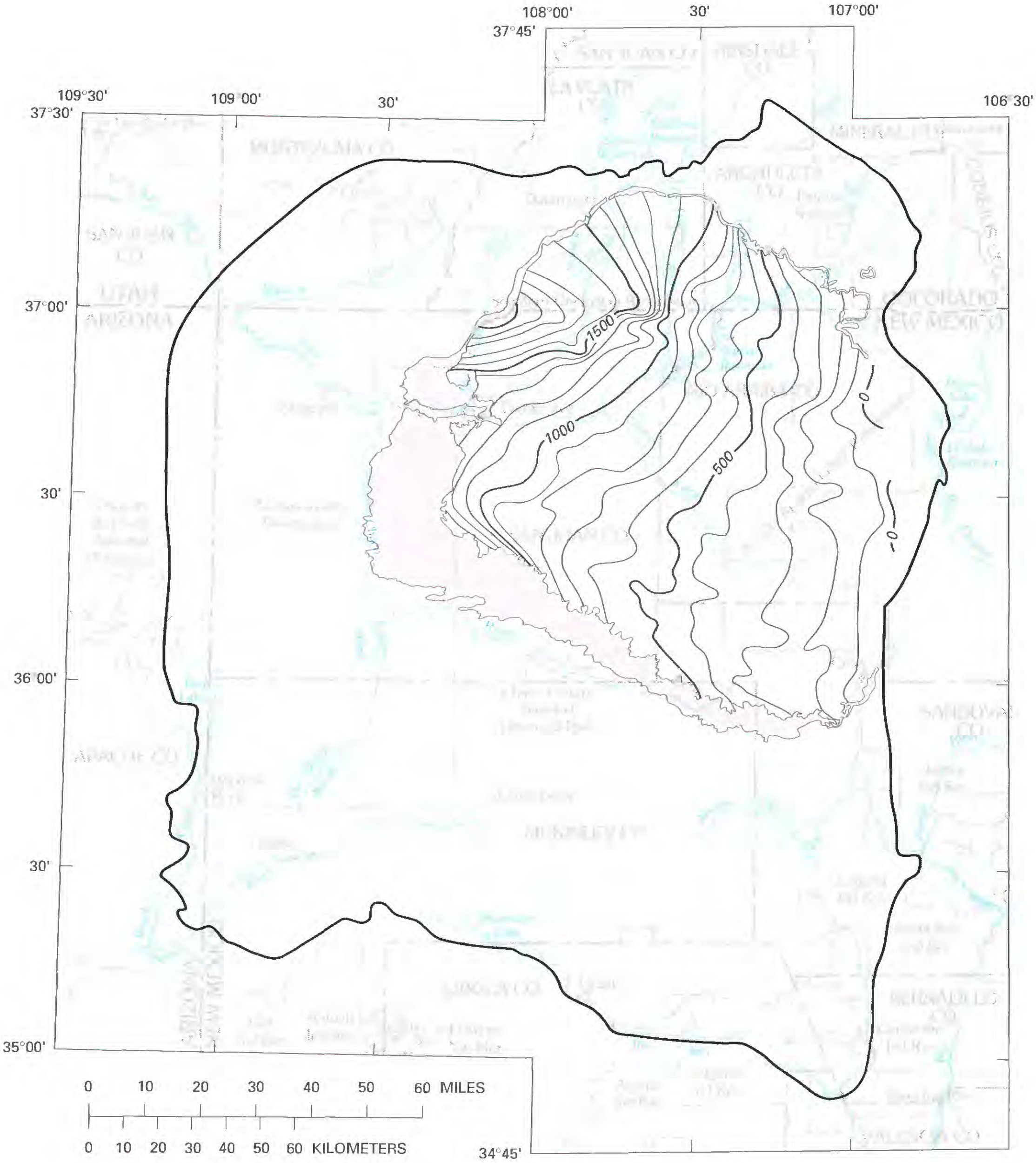
Tertiary rocks were deposited in various nonmarine (stream channel, flood plain, eolian, and lacustrine) environments. The maximum combined thickness of these rocks in the Central Basin is about 3,800 feet; the thickness of the strata in the Central Basin generally increases toward the east. The general lithologies and thicknesses of Tertiary rocks are summarized in table 1; their outcrops are shown on plate 1.

OJO ALAMO SANDSTONE

The Ojo Alamo Sandstone is of Paleocene age (fig. 5). It crops out inside the Central Basin (pl. 1) and typically forms cliffs and dip slopes or caps low mesas and forms rounded hills. The majority of Ojo Alamo rocks are in New Mexico. The formation pinches out in the northwest, about halfway between Farmington and the Colorado State line, west of La Plata River. In the northeast, Ojo Alamo outcrops can be traced into Colorado, where the formation pinches out a few miles north of the State line, south of Pagosa Springs (Fassett, 1974, p. 228). Subsurface studies by Fassett and Hinds (1971, fig. 9 and p. 29) indicate that the Ojo Alamo is not present north of a line connecting the northernmost outcrops of the formation.

Throughout most of its extent, the Ojo Alamo Sandstone disconformably overlies the Kirtland Shale. On the east side of the Central Basin, however, the Kirtland was completely eroded prior to deposition of the Ojo Alamo, and the Ojo Alamo disconformably overlies the Fruitland Formation; locally, in places where the Fruitland has been completely eroded, the Ojo Alamo disconformably overlies the Lewis Shale (Fassett, 1974, p. 228). The contact of the Ojo Alamo with underlying rocks has been described by O'Sullivan and others (1972, p. 56) as a distinct, wavy erosional surface. Fassett and Hinds (1971, p. 28) reported large-scale channeling at the base of the Ojo Alamo and stated that some of these channels extend 50 feet or more into the underlying shale or sandstone of the Fruitland Formation or Kirtland Shale. Throughout most of its extent, the Ojo Alamo is conformably overlain by the Nacimiento Formation, and intertonguing at the contact is common (Fassett and Hinds, 1971, p. 29).

Strata of the Ojo Alamo Sandstone primarily represent overlapping stream-channel deposits (Baltz, 1967, p. 33), but flood-plain deposits also are present (Powell, 1973, p. 116). Powell (1973) presented an alluvial-plain depositional model for the formation. In general, the Ojo Alamo consists of overlapping sheetlike sequences of sandstone and conglomeratic sandstone that locally contain interbedded shale lenses. The sandstone is arkosic, light brown to rusty brown or buff and tan, and contains abundant silicified wood. The sandstone is medium to very coarse grained and commonly conglomeratic, containing pebbles of various compositions that decrease in size and quantity from west to east across



EXPLANATION

Outcrops of Kirtland Shale and Fruitland Formation, undivided—From Dane and Bachman (1965) and Tweto (1979)

Boundary of study area

1000 **Line of equal thickness of the Kirtland Shale and Fruitland Formation, undivided**—From Fassett and Hinds (1971). Interval 100 feet

FIGURE 25.—Approximate thickness of the combined Fruitland Formation and Kirtland Shale in the San Juan Basin study area. Modified from Fassett and Hinds (1971, fig. 11).

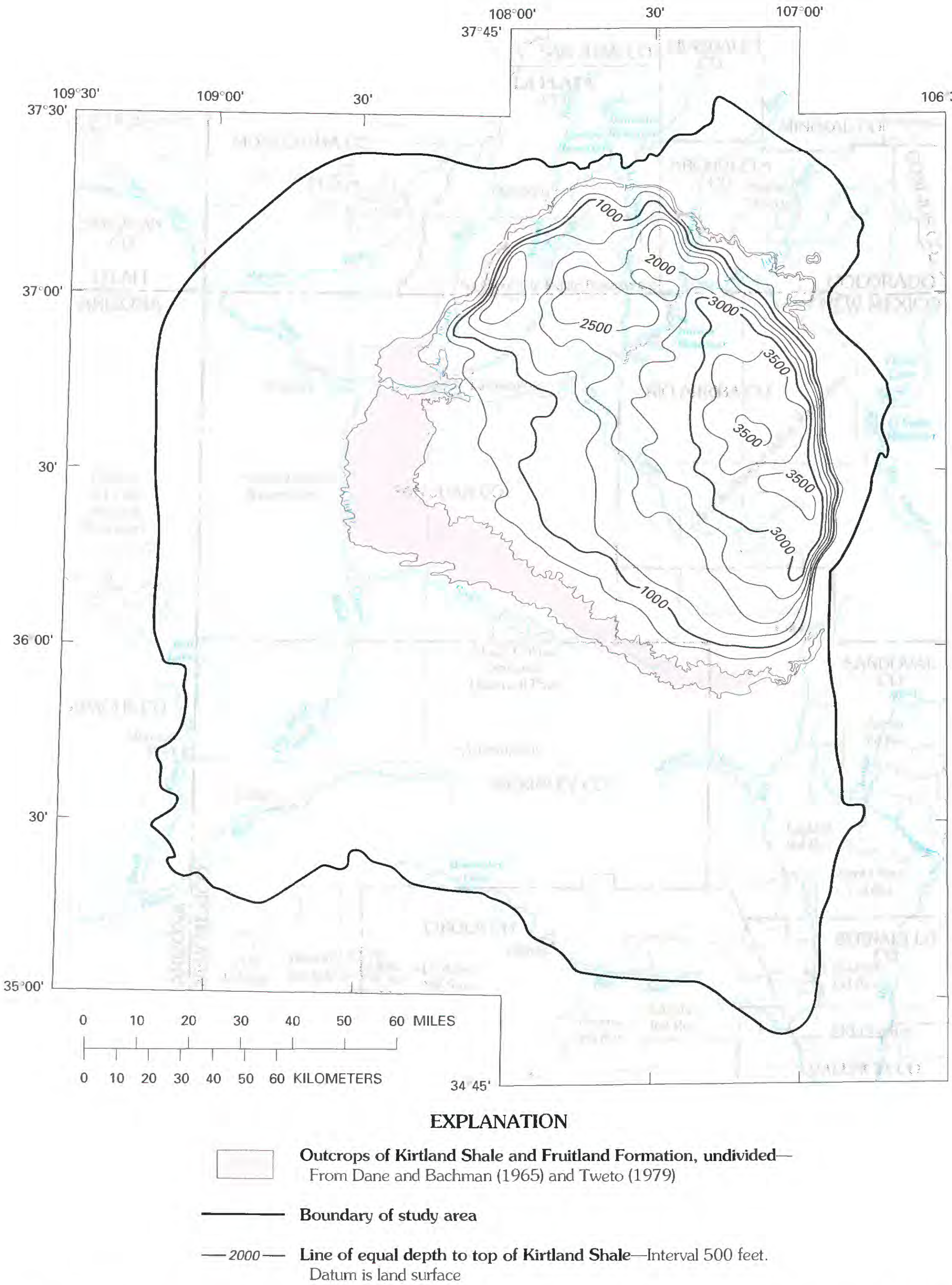
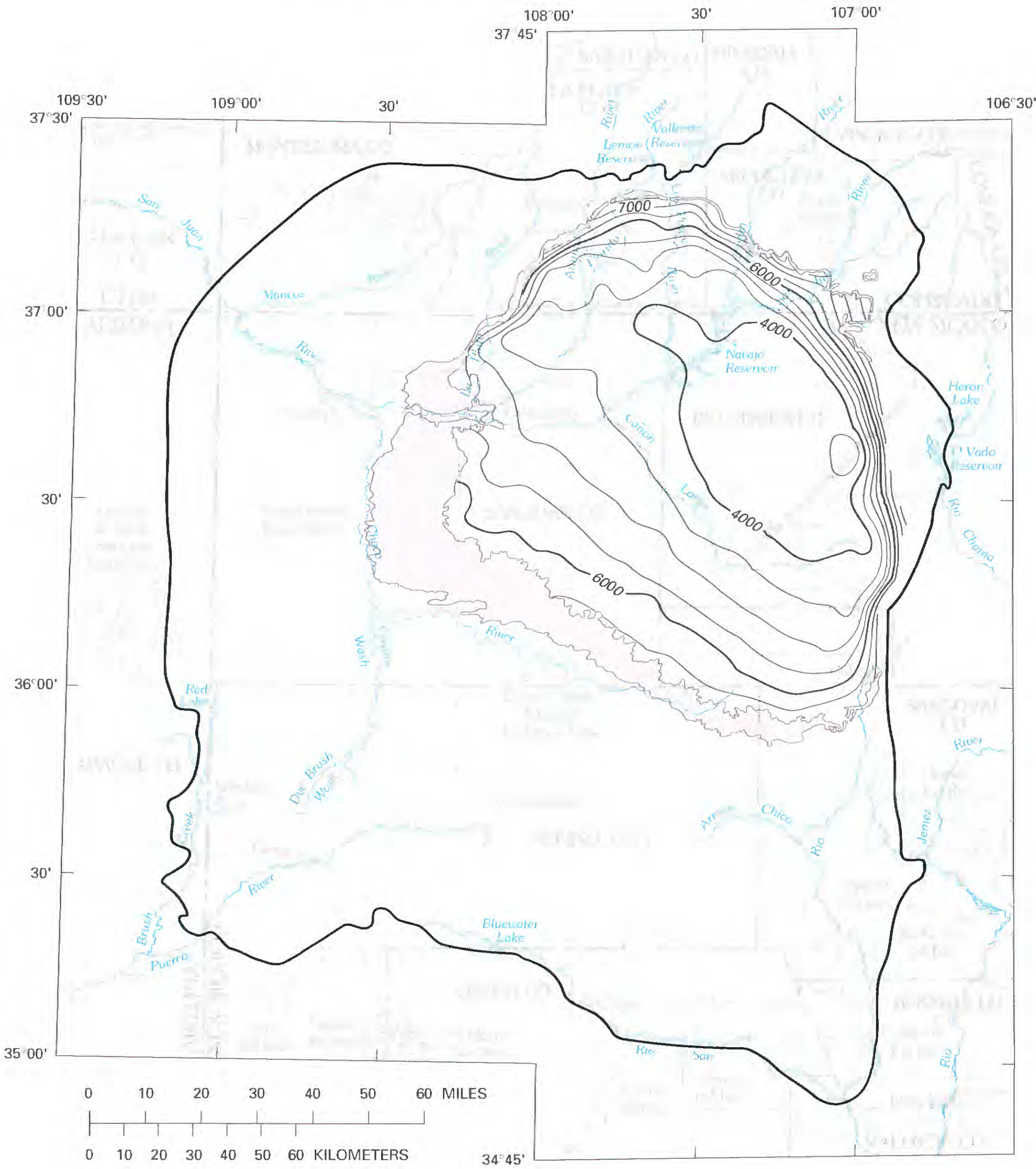


FIGURE 26.—Approximate depth to the top of the combined Fruitland Formation and Kirtland Shale in the San Juan Basin study area. Modified from Kernodle and others (1990).



EXPLANATION

Outcrops of Kirtland Shale and Fruitland Formation, undivided—From Dane and Bachman (1965) and Tweto (1979)

Boundary of study area

—4000— **Structure contour**—Shows altitude of top of Kirtland Shale. Contour interval 500 feet. Datum is sea level

FIGURE 27.—Approximate altitude and configuration of the top of the combined Fruitland Formation and Kirtland Shale in the San Juan Basin study area. Modified from Kernodle and others (1990).

the Central Basin (Baltz and West, 1967, p. 17; Fassett and Hinds, 1971, p. 28). The Ojo Alamo Sandstone is a dependable aquifer and yields water to wells and springs mainly in its outcrop area (Brimhall, 1973, p. 199–202; Brown, 1976, p. 52; Anderholm, 1979, p. 29–33; Cooley and Weist, 1979, p. 45).

The thickness of the Ojo Alamo Sandstone is variable. Baltz (1967, p. 32) reported that the thickness ranges from 70 to 200 feet. O'Sullivan and others (1972, p. 57) also reported a maximum thickness of 200 feet, whereas Stone and others (1983, p. 31) reported a thickness range of 70–300 feet. Fassett and Hinds (1971, p. 28, 29) reported that throughout the Central Basin, the thickness of the Ojo Alamo ranges from 20 to 400 feet but that a range of 50–150 feet is most common. Fassett and Hinds (1971, p. 28) also stated that thickness varies according to the number of sandstone beds that constitute the formation at any given location.

The depth to the top of the Ojo Alamo Sandstone ranges from outcrops to about 3,500 feet in the east-central part of the Central Basin (fig. 28). The altitude and configuration of the top of the Ojo Alamo is shown in figure 29. The top surface decreases from a maximum altitude of about 8,000 feet above sea level along the narrow outcrop band in the northeast to about 4,000 feet above sea level in the subsurface in the east-central part of the study area.

ANIMAS FORMATION

Most of the Animas Formation is of Paleocene age, but the lower part is of latest Late Cretaceous age (fig. 5) (Barnes and others, 1954). The formation crops out principally inside the northern margin of the Central Basin (pl. 1). The Animas is present only in the northern part of the Central Basin, mainly in Colorado, where it is found south of a zone that connects Dulce, N. Mex., and La Plata River valley near the New Mexico-Colorado State line. Along this zone, the Animas grades laterally into and occupies the same stratigraphic interval as the Nacimiento Formation (fig. 5) (Fassett and Hinds, 1971, p. 34; Fassett, 1974, p. 229). The Animas conformably overlies the Kirtland Shale in the north; farther south (near the New Mexico-Colorado State line), the upper part of the formation might unconformably overlie the Ojo Alamo Sandstone (Fassett and Hinds, 1971, p. 34).

The Animas Formation consists of the McDermott Member of Late Cretaceous age and the unnamed upper member of Paleocene age (fig. 5) (Barnes and others, 1954). The upper member disconformably overlies the McDermott Member, the unconformity representing a hiatus of about 6 million years (Fassett, 1988b, p. 319). The Animas Formation mainly consists of fluvial and volcaniclastic deposits. The McDermott Member is present only in the Animas River valley area of Colorado and is laterally equivalent to the upper shale member of the Kirtland Shale. The McDermott Member consists of varicolored (dominantly purple) tuffaceous sandstone and conglomerate with some variegated shale (Reeside, 1924, p. 25). The upper member is present in New Mexico and Colorado and also consists of varicolored and interbedded tuffaceous sandstone, conglomerate, and shale (Fassett, 1974, p. 229). The diagnostic characteristic of the Animas Formation is the presence of macroscopic volcanic material (Fassett and Hinds, 1971, p. 33).

The thickness of the Animas Formation ranges from about 230 feet at the stratotype along the Animas River at Durango (Barnes and others, 1954), to about 2,700 feet near the La Plata-Archuleta County line in Colorado (Fassett and Hinds, 1971, p. 33). The Animas could be expected to yield small quantities of water to wells, with water-yielding characteristics similar to those of the Nacimiento Formation (Cooley and Weist, 1979, p. 44).

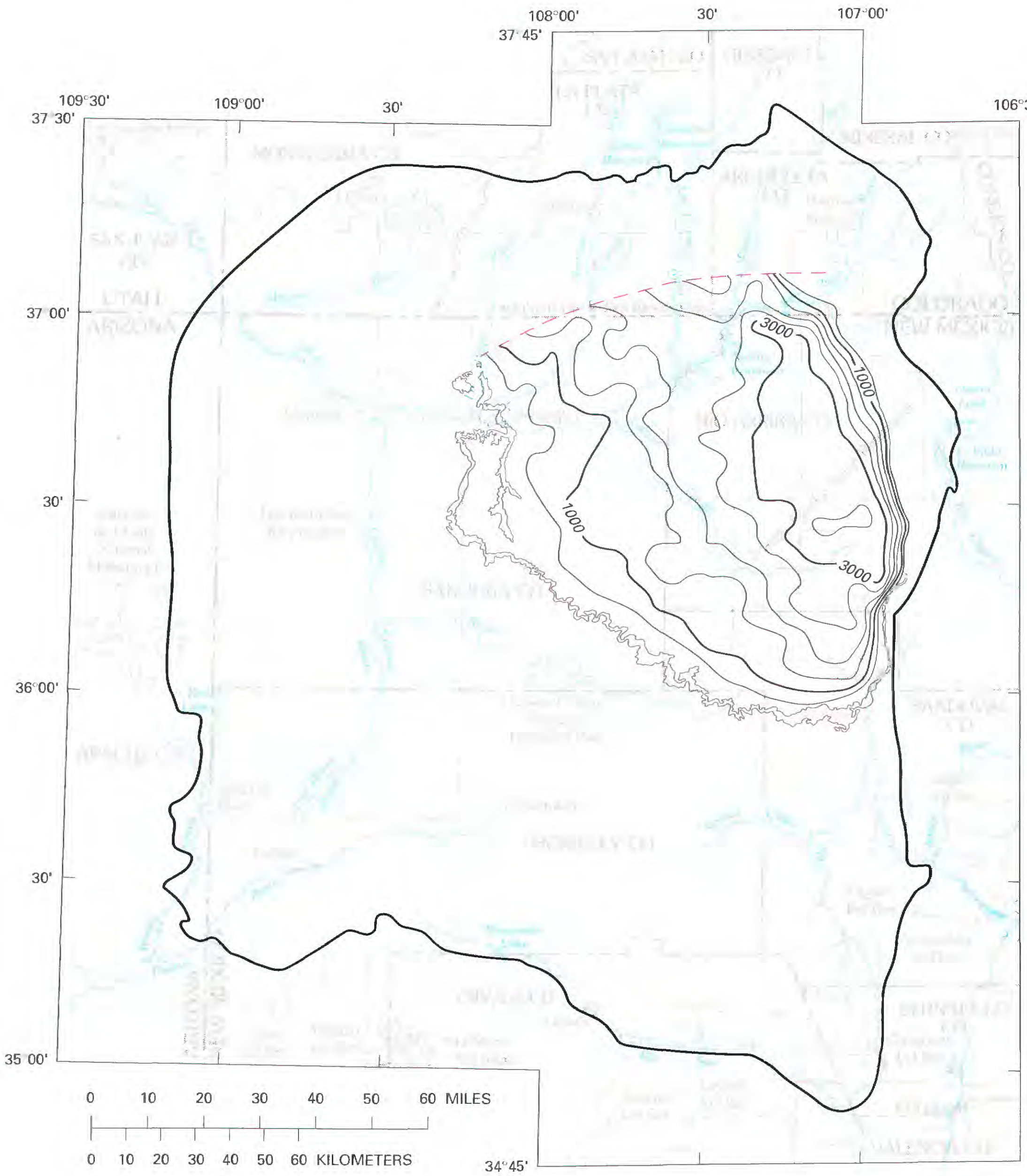
NACIMIENTO FORMATION

The Nacimiento Formation is of Paleocene age (Baltz, 1967, p. 35). It crops out principally in a broad band inside the southern and western margins of the Central Basin and also in a narrow band along the western face of the Nacimiento Uplift (pl. 1). The Nacimiento is a nonresistant unit and typically erodes to low, rounded hills or forms badlands topography.

The Nacimiento Formation is present in the southern two-thirds of the Central Basin where it conformably overlies and intertongues with the Ojo Alamo Sandstone (Baltz, 1967, p. 41; Fassett, 1974, p. 229). Along a zone connecting Dulce and the La Plata River valley near the New Mexico-Colorado State line, the Nacimiento grades laterally into the upper part of the Animas Formation (Fassett and Hinds, 1971, p. 34; Fassett, 1974, p. 229). Along this zone, the two formations occupy the same stratigraphic interval (fig. 5).

Strata of the Nacimiento Formation mainly were deposited in lakebeds, with lesser deposition in stream channels (Brimhall, 1973, p. 201; Fassett, 1974, p. 229). In general, the strata consist of drab, interbedded black and gray shale with discontinuous white, medium- to very coarse grained arkosic sandstone (Fassett, 1974, p. 229; Stone and others, 1983, p. 30). Anderholm (1979, p. 25) reported local carbonaceous shale and lignite in the formation. Baltz (1967, p. 39) stated that the sandstone percentage increases northward. Stone and others (1983, p. 30) suggested that the formation might contain more sandstone than is often reported because some geologists might have assumed the slope-forming strata in the unit to be shale, whereas in some localities these strata actually are poorly consolidated sandstone.

The thickness of the Nacimiento Formation ranges from 500 to 1,300 feet (Molenaar, 1977a). The formation generally thickens from the Central Basin margins toward the center (Baltz, 1967, p. 38; Steven and others, 1974; Stone



EXPLANATION

Outcrops of Ojo Alamo Sandstone—From Dane and Bachman (1965) and Fassett and Hinds (1971)

Approximate subsurface extent of Ojo Alamo Sandstone—From Fassett and Hinds (1971)

Boundary of study area

1000 **Line of equal depth to top of Ojo Alamo Sandstone**—Interval 500 feet. Datum is land surface

FIGURE 28.—Approximate depth to the top of the Ojo Alamo Sandstone in the San Juan Basin study area. Modified from Thorn and others (1990b).

EXPLANATION

Outcrops of Ojo Alamo Sandstone—From Dane and Bachman (1965) and Fassett and Hinds (1971)

Approximate subsurface extent of Ojo Alamo Sandstone—From Fassett and Hinds (1971)

Boundary of study area

—4000— **Structure contour**—Shows altitude of top of Ojo Alamo Sandstone. Contour interval 500 feet. Datum is sea level

FIGURE 29.—Approximate altitude and configuration of the top of the Ojo Alamo Sandstone in the San Juan Basin study area. Modified from Thorn and others (1990b).

and others, 1983), but the thickness and extent of sandstone-lenses lessen because their depositional environment was in the more localized stream channels (Brimhall, 1973, p. 201).

Discontinuous, fine-grained sandstone bodies in the Nacimiento Formation yield variable quantities of water to wells; however, the formation is only dependable as a local aquifer (Brimhall, 1973, p. 201). Cooley and Weist (1979, p. 44) reported that the Nacimiento probably is a better aquifer toward the northeast, where sandstone becomes more prevalent. Brown (1976, p. 43, 44) and Anderholm (1979, p. 25, 27) also reported on the water-yielding characteristics of the Nacimiento.

SAN JOSE FORMATION

The San Jose Formation of Eocene age was defined by Simpson (1948a, b). With the exception of the isolated Chuska Sandstone near the western edge of the study area, the San Jose Formation is the youngest sedimentary rock unit in the San Juan Basin, and its outcrops form the land surface throughout much of the Central Basin area (pl. 1).

The San Jose Formation is present in New Mexico and Colorado. It generally overlies the Nacimiento Formation south of the State line and overlies the Animas Formation north of the State line (Fassett, 1974, p. 229). The basal contact of the San Jose Formation varies with location in the San Juan Basin. Along the basin margins, this contact is a disconformity whereas along the Nacimiento Uplift it is an angular unconformity; in the Central Basin, the contact is conformable (Baltz, 1967, p. 54; Fassett, 1974, p. 229).

The San Jose Formation was deposited in various fluvial environments (Baltz, 1967, p. 44–55) and consists of an interbedded sequence of sandstone, siltstone, and variegated shale. The sandstone is buff to yellow and rust colored, crossbedded, very fine to coarse-grained arkose that is locally conglomeratic and contains abundant silicified wood (Baltz, 1967, p. 46; Fassett, 1974, p. 229; Anderholm, 1979, p. 23).

Baltz (1967, p. 45) recognized four members of the San Jose Formation in the east-central part of the Central Basin. These members and their principal lithologies are (in ascending order) the Cuba Mesa Member (sandstone), Regina Member (shale), Llaves Member (sandstone), and Tapicitos Member (shale). Baltz (1967) also identified but did not name a fifth member in the northeastern part of the Central Basin, The stratigraphic relations and consequent mappability of these members are complicated by extensive intertonguing and pinch outs (Fassett, 1974, p. 229; Anderholm, 1979, p. 23; Stone and others, 1983, p. 25). Whether the members are regionally mappable throughout the Central Basin has been the subject of some discussion among San Juan Basin geologists.

The thickness of the San Jose Formation is variable but generally increases from west to east. Fassett (1974, p. 229) reported a maximum thickness of 2,400 feet in the east-central part of the Central Basin, and Stone and others (1983, p. 25) reported a range from about 200 feet in the west and south to almost 2,700 feet in the center of the Central Basin.

Brimhall (1973, p. 202) and Stone and others (1983, p. 25) reported that the sandstones of the San Jose Formation are largely untested as aquifers. Baltz and West (1967, p. 62) and Brown (1976, p. 33, 35) stated that the San Jose should be considered as a major water source. Anderholm (1979, p. 24) reported that the Cuba Mesa Member has good potential for yielding water to wells on the eastern side of the San Juan Basin.

UNDIVIDED TERTIARY SEDIMENTARY ROCKS ABOVE THE OJO ALAMO SANDSTONE IN THE CENTRAL BASIN

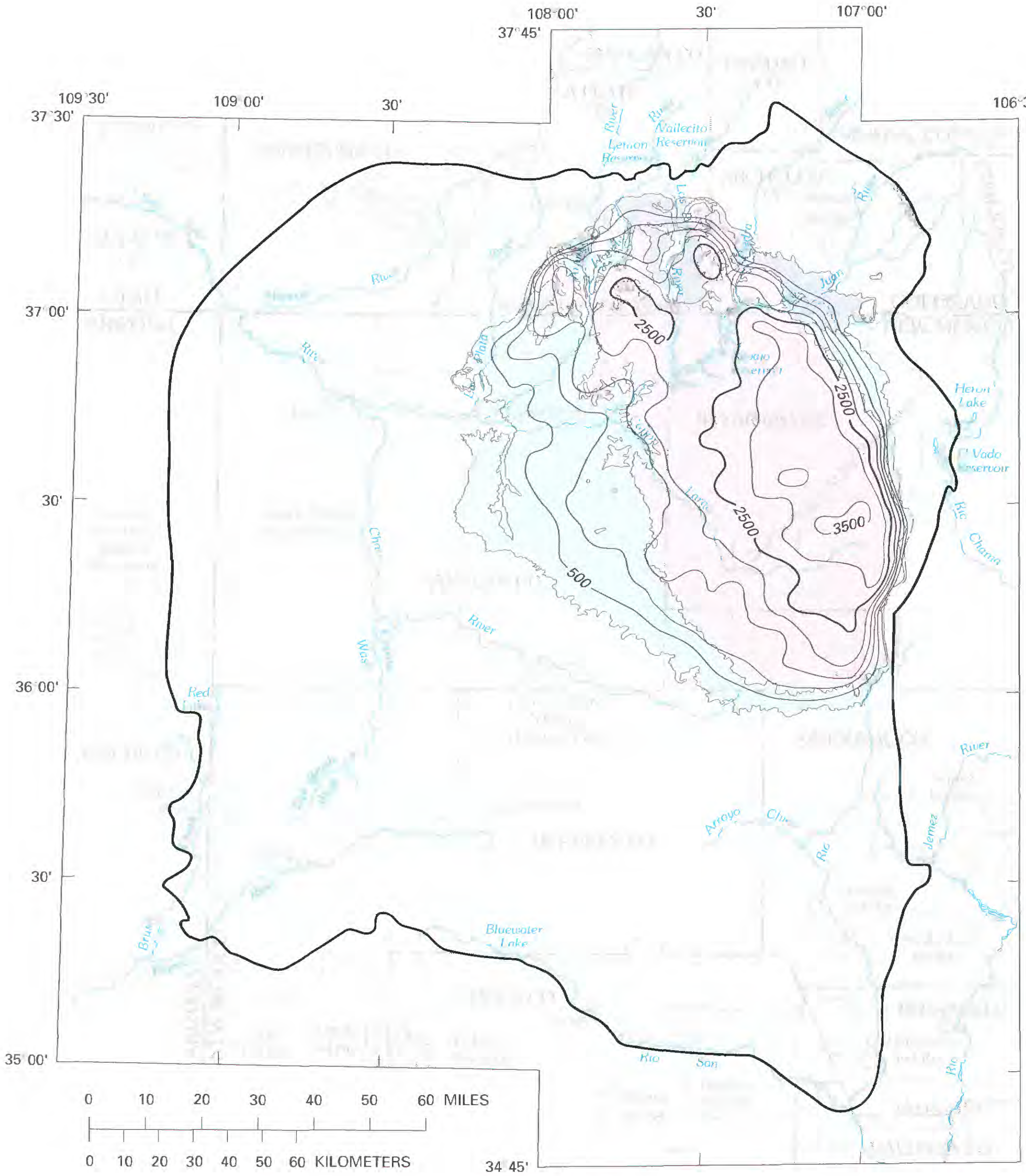
The thickness of the undivided Tertiary sedimentary rocks above the Ojo Alamo Sandstone in the Central Basin (including the McDermott Member of the Animas Formation) is shown in figure 30. The thickness ranges from about 500 to about 3,500 feet in the east-central part of the Central Basin.

The altitude and configuration of the bottom of the undivided Tertiary sequence (actually, the undivided Nacimiento and Animas Formations) above the Ojo Alamo Sandstone in the Central Basin is shown in figure 31. The bottom of these rocks decreases from a maximum altitude of about 8,000 feet above sea level in the northeast to about 4,000 feet above sea level in the east-central part of the Central Basin.

CHUSKA SANDSTONE

The Chuska Sandstone was originally described by Gregory (1916, pl. 21) as being of Eocene(?) age. Later investigations, however, determined the unit to be at least as young as early Oligocene (Hackman and Olson, 1977). As such, the Chuska is the youngest sedimentary rock unit in the San Juan Basin but is restricted to the western part of the basin, where it caps the Chuska Mountains along the New Mexico-Arizona State line (pl. 1).

The Chuska Sandstone unconformably overlies Mesozoic sedimentary rocks along the Defiance Monocline. The unit was deposited principally in an eolian environment but also contains deposits of fluvial origin in the lower part. In general, the Chuska consists of friable, light-brown, yellowish-gray, or white, massive, crossbedded, very fine to coarse-grained sandstone; some interbeds of reddish-brown siltstone and shale also are present (O'Sullivan and Beikman, 1963; Hackman and Olson, 1977). Locally, the lower part of the Chuska consists of as much as 250 feet of fluvial sandstone and shale and was formerly referred to as the Deza Formation (Wright, 1956). Because of sparse distribution of



EXPLANATION

Outcrops of San Jose Formation—From Dane and Bachman (1965), and Tweto (1979)

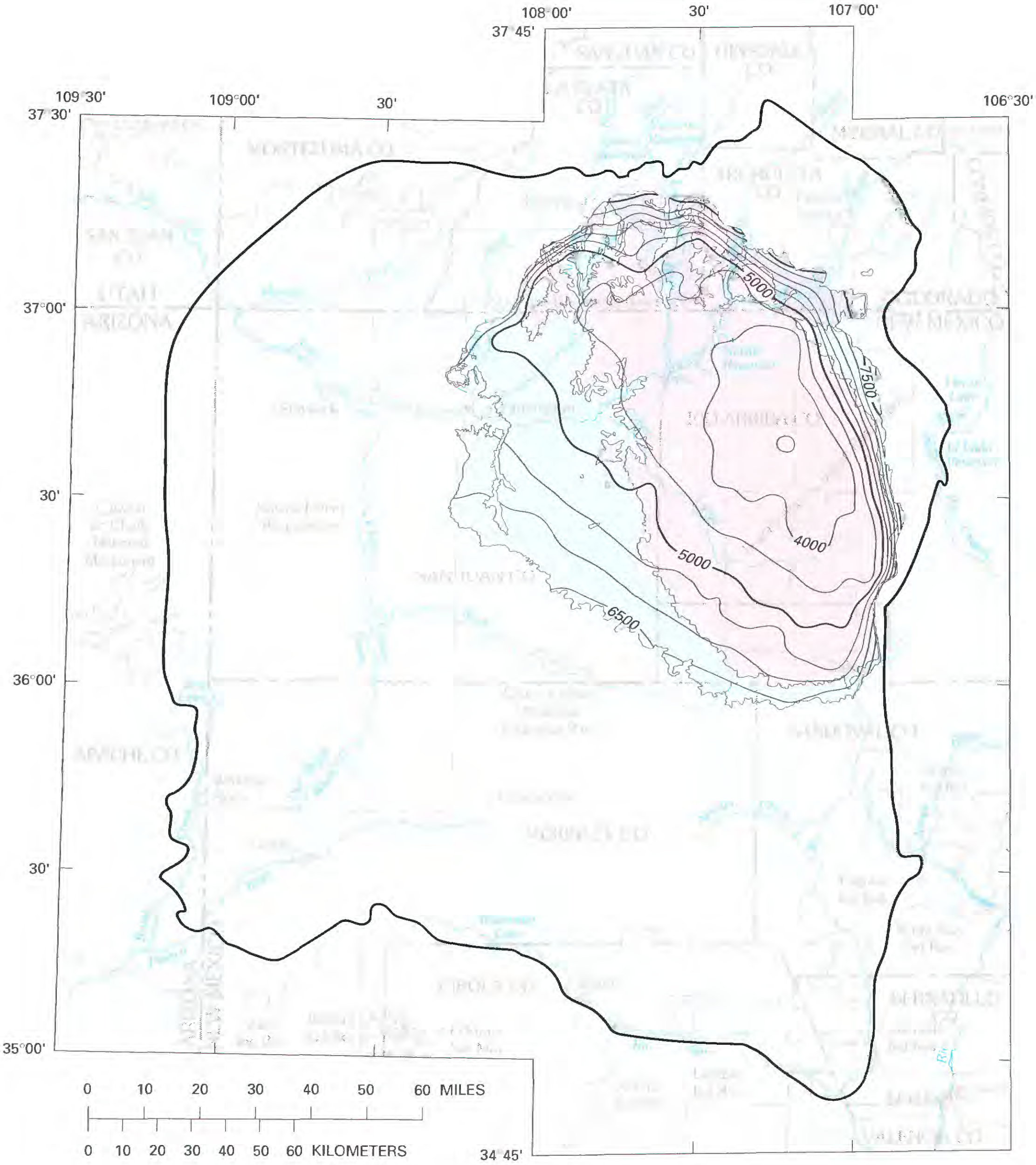
Outcrops of Nacimiento Formation—From Dane and Bachman (1965), Fassett (1974), and Tweto (1979)

Outcrops of Animas Formation—From Dane and Bachman (1965), Fassett (1974), and Tweto (1979)

Boundary of study area

—2500— Line of equal thickness of San Jose, Nacimiento, and Animas Formations—Interval 500 feet

FIGURE 30.—Approximate thickness of the undivided Tertiary sedimentary rocks above the Ojo Alamo Sandstone in the Central Basin of the San Juan Basin. Modified from Levings and others (1990b).



EXPLANATION

Outcrops of San Jose Formation—From Dane and Bachman (1965) and Tweto (1979)

Outcrops of Nacimiento Formation—From Dane and Bachman (1965), Fassett (1974), and Tweto (1979)

Outcrops of Animas Formation—From Dane and Bachman (1965), Fassett (1974), and Tweto (1979)

Boundary of study area

—*4000*— **Structure contour**—Shows altitude of bottom of Nacimiento and Animas Formations. Contour interval 500 feet. Datum is sea level

FIGURE 31.—Approximate altitude and configuration of the bottom of the undivided Tertiary sedimentary rocks above the Ojo Alamo Sandstone in the Central Basin of the San Juan Basin. Modified from Levings and others (1990b).

outcrops and questionable mappability, the name Deza Formation has been abandoned.

The Chuska Sanstone's thickness throughout most of the Chuska Mountains ranges from 500 to 1,200 feet, but Wright (1956, p. 416) reported a maximum local thickness of about 1,750 feet. Cooley and Weist (1979, p. 42) stated that water wells have not been completed in the Chuska Sandstone, but the formation yields water to many springs in the Chuska Mountains (Lyford, 1979, p. 16).

SUMMARY

The San Juan Basin, with an area of about 21,600 square miles, encompasses northwestern New Mexico, southwestern Colorado, northeastern Arizona, and southeastern Utah. The basin is a structural depression formed during the Laramide orogeny; maximum structural relief is about 10,000 feet. A Cambrian through Tertiary sedimentary rock sequence about 14,400 feet thick fills the basin.

The RASA study area that is the subject of this report consists of that part of the basin that contains Triassic through Tertiary sedimentary rocks; it is somewhat smaller (about 19,400 square miles) than the structural basin. The older Triassic rocks crop out around the basin margins and are sequentially overlain by Jurassic, Cretaceous, and Tertiary rocks toward the center of the basin. These strata dip toward the troughlike center, the structurally deepest part of the basin.

Triassic rocks represent deposition in various nonmarine environments and consist of the Moenkopi, Moenkopi(?), Chinle, and Dolores Formations. Triassic strata attain a maximum combined thickness of about 1,650 feet in the west-central part of the basin. Because of its limited areal extent, the Moenkopi Formation is not an important aquifer in the basin. Regionally, the Chinle and Dolores Formations act as confining units, but local sandstone bodies are water yielding.

Jurassic rocks also were deposited in continental environments and attain a maximum combined thickness of about 1,500 feet in the northwestern part of the basin. Jurassic formations include the Wingate Sandstone, Entrada Sandstone, Wanakah Formation, Cow Springs Sandstone, Morrison Formation, and Junction Creek Sandstone. The Wingate Sandstone is unimportant as an aquifer because of its limited areal extent, but parts of the other formations are water yielding. The Westwater Canyon Member of the Morrison Formation is regionally the most productive aquifer in the Jurassic strata.

Cretaceous rocks were deposited in continental, marginal marine, and marine environments associated with several advances and retreats of a large, shallow inland seaway that bisected the continent. Cretaceous rocks attain a combined thickness of at least 6,500 feet in the San Juan Basin. The strata include the Burro Canyon Formation, Dakota Sandstone, Mancos Shale, Gallup Sandstone, Crevasse Canyon Formation, Point Lookout Sandstone, Menefee Formation, Cliff House Sandstone, Lewis Shale, Pictured Cliffs Sandstone, Fruitland Formation, and Kirtland Shale. The McDermott Member of the Animas Formation also is of Cretaceous age. Although parts of all these formations are water yielding, the Dakota and Gallup Sandstones are regionally the most productive aquifers in Cretaceous rocks.

Tertiary sedimentary rocks represent deposition in various nonmarine environments and in the Central Basin include the Ojo Alamo Sandstone, upper part of the Animas Formation, Nacimiento Formation, and San Jose Formation. Maximum combined thickness of these rocks is about 3,800 feet. In the west-central part of the San Juan Basin, the Chuska Sandstone, the youngest sedimentary unit in the basin, caps the Chuska Mountains and attains a maximum thickness of about 1,800 feet. The most productive aquifers in Tertiary rocks are the Ojo Alamo Sandstone and sandstone bodies in the San Jose Formation.

Geologic maps showing the thickness, depth to the top, and altitude and configuration of the top of major formations were prepared from a data base of about 24,000 oil- and gas-test wells in the basin, supplemented with water-well data from the U.S. Geological Survey's NWIS data base and data from outcrops. These maps were constructed using a surface-contour-generating package interfaced with a Geographic Information System. The maps were used as input to a three-dimensional, ground-water flow model of the regional aquifer system in the San Juan Basin.

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APPENDIX

APPENDIX—METHOD OF CONTOURING MAPS USING SURFACE MODELING AND GEOGRAPHIC INFORMATION SYSTEM SOFTWARE

A surface-contour-generating software package, Interactive Surface Modeling (ISM) by Dynamics Graphics, Inc., was used to construct geologic contour maps (subsurface altitude and configuration of the top, depth to the top and, if possible, thickness) of major formations in the San Juan Basin. An interface was developed between ISM and Environmental Systems Research Institute's ARC/INFO Geographic Information System. The contour maps were converted to ARC/INFO polygon coverages for later input to a digital, three-dimensional ground-water flow model of the regional aquifer system in the basin; these techniques were discussed in detail by Kernodle and Philip (1988).

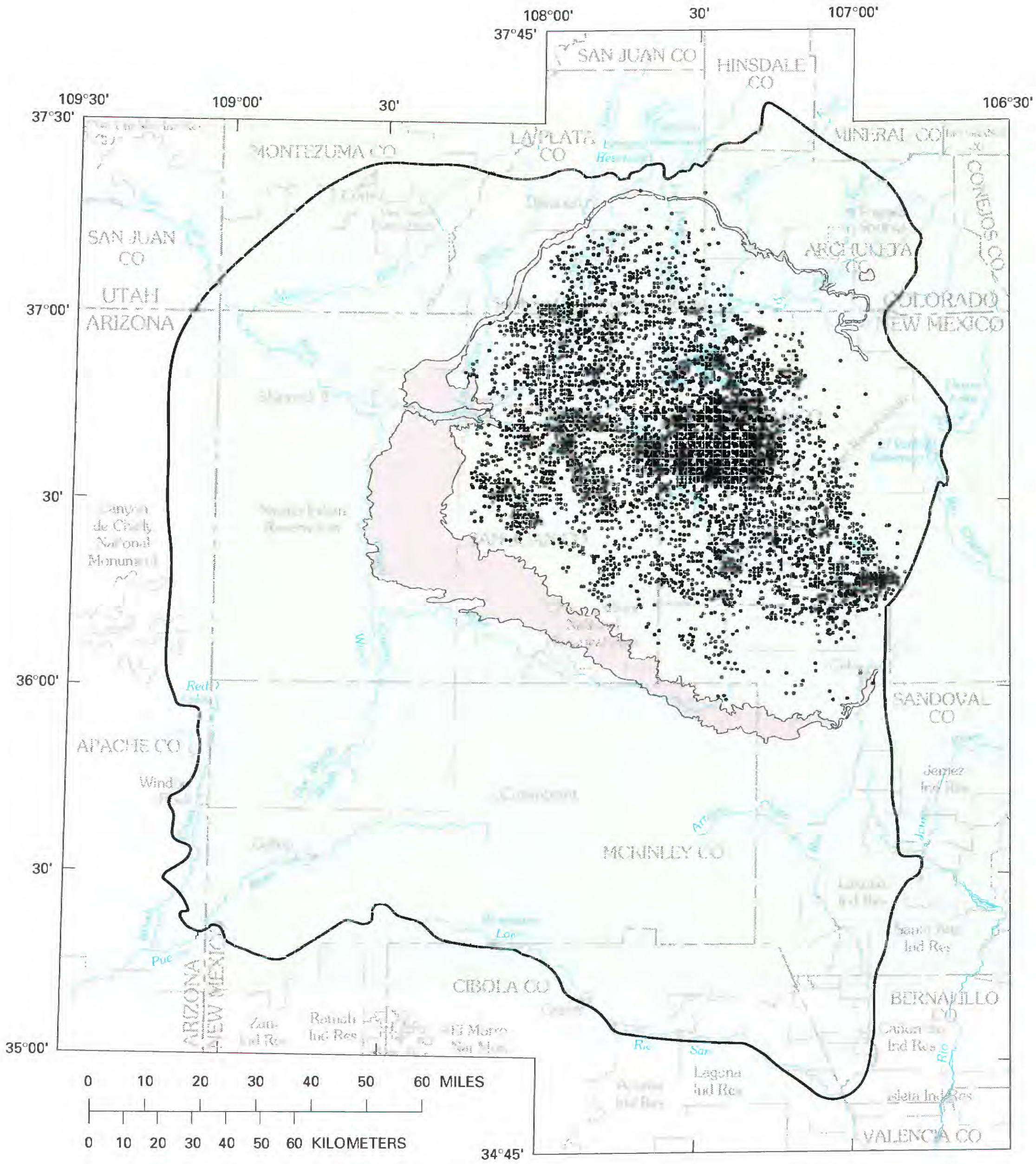
The general process of preparing geologic contour maps is discussed below and illustrated in figures 32–34. The process illustrated here is for the preparation of maps of the combined Fruitland Formation and Kirtland Shale, but the same process was used for the other formations. Data points used to generate the maps were derived from 10 U.S. Geological Survey Hydrologic Investigations Atlases prepared during the San Juan Basin RASA (see Craigg and others, 1989, 1990; Kernodle and others, 1989, 1990; Dam and others, 1990a, b; Levings and others, 1990a, b; and Thorn and others, 1990a, b). The Petroleum Information Corporation's data base of about 24,000 oil- and gas-test wells in the San Juan Basin was used in the computerized data-retrieval process. Only the reported altitudes of the tops of formations picked from geophysical logs were selected from this data base. The data were evaluated for accuracy by comparing the altitude above sea level of each selected formation top on the logs with the mean value of the formation tops of neighboring wells. This was accomplished by intersecting an ARC/INFO point coverage of the wells with a polygon coverage of a fine-mesh grid (fig. 32 shows this intersection for wells having an altitude for the top of the combined Fruitland Formation and Kirtland Shale; grid size is about 0.6 square mile). Wells were collected by grid cell, and a mean value of the altitude was determined for each cell. Points with formation tops that differed from the local mean by 50 or more feet were assumed to be erroneous and were deleted from the data file for each formation.

After a satisfactory contour map was produced and converted to ARC/INFO coverage, the ARC/INFO system was used to edit contours (if necessary), to annotate contours, and to clip (a "cookie-cutter" routine) the contour coverage with a polygon coverage of the inner (basinward) part of the appropriate geologic outcrop (figs. 33 and 34). The contour map was then combined with a base map of other ARC/INFO geographic coverages (hydrography, outcrop, political boundaries, study area, structural basin, and roads), produced in hard-copy format, and published in U.S. Geological Survey Hydrologic Investigations Atlases HA–720–A through J Craigg and others, 1989, 1990; Dam and others, 1990a, b; Kernodle and others, 1989, 1990; Levings and others, 1990a, b; and Thorn and others, 1990a, b).

The techniques described above for preparing regional geologic contour maps were useful tools during the San Juan Basin RASA for defining the geologic framework of the basin's multilayered aquifer system. In turn, this framework provided the basis for the ground-water-flow modeling part of this RASA investigation as well as a basis for future regional and local hydrogeologic studies of this basin. These techniques and their modification and refinement also should have transfer value to other hydrogeologic studies.

It is important, however, that the investigator be experienced and knowledgeable about the geology of the study area and its relation to the ground-water-flow system(s). A conceptual framework of the hydrogeology of the study area needs to be developed before any digital-mapping techniques are used. The hydrogeologist needs to be able to recognize reasonable and erroneous results immediately, regardless of how impressive and attractive the maps might be. These important concepts also were expressed by Berry (1987) in an informative discussion of some of the pitfalls to be avoided in the production of computer-generated maps.

In summary, computerized analysis of large quantities of geologic data using a Geographic Information System coupled with surface-modeling software (a geoscience information system) and the resulting contour maps representing various aspects of the hydrogeologic framework of an area have important application to the science of hydrogeology. But it also is important that the resulting maps never be "untouched by the human mind."



EXPLANATION

Outcrops of Kirtland Shale and Fruitland Formation, undivided—From Dane and Bachman (1965) and Tweto (1979)

Geographic Information System polygon coverage of fine-mesh grid

Boundary of study area

Control point—Used to compute approximate altitude of the top of the combined Kirtland Shale and Fruitland Formation

FIGURE 32.—Geographic Information System coverage of control points intersected with a fine-mesh grid used to compute approximate altitude and configuration of the top of the combined Fruitland Formation and Kirtland Shale in the San Juan Basin study area.

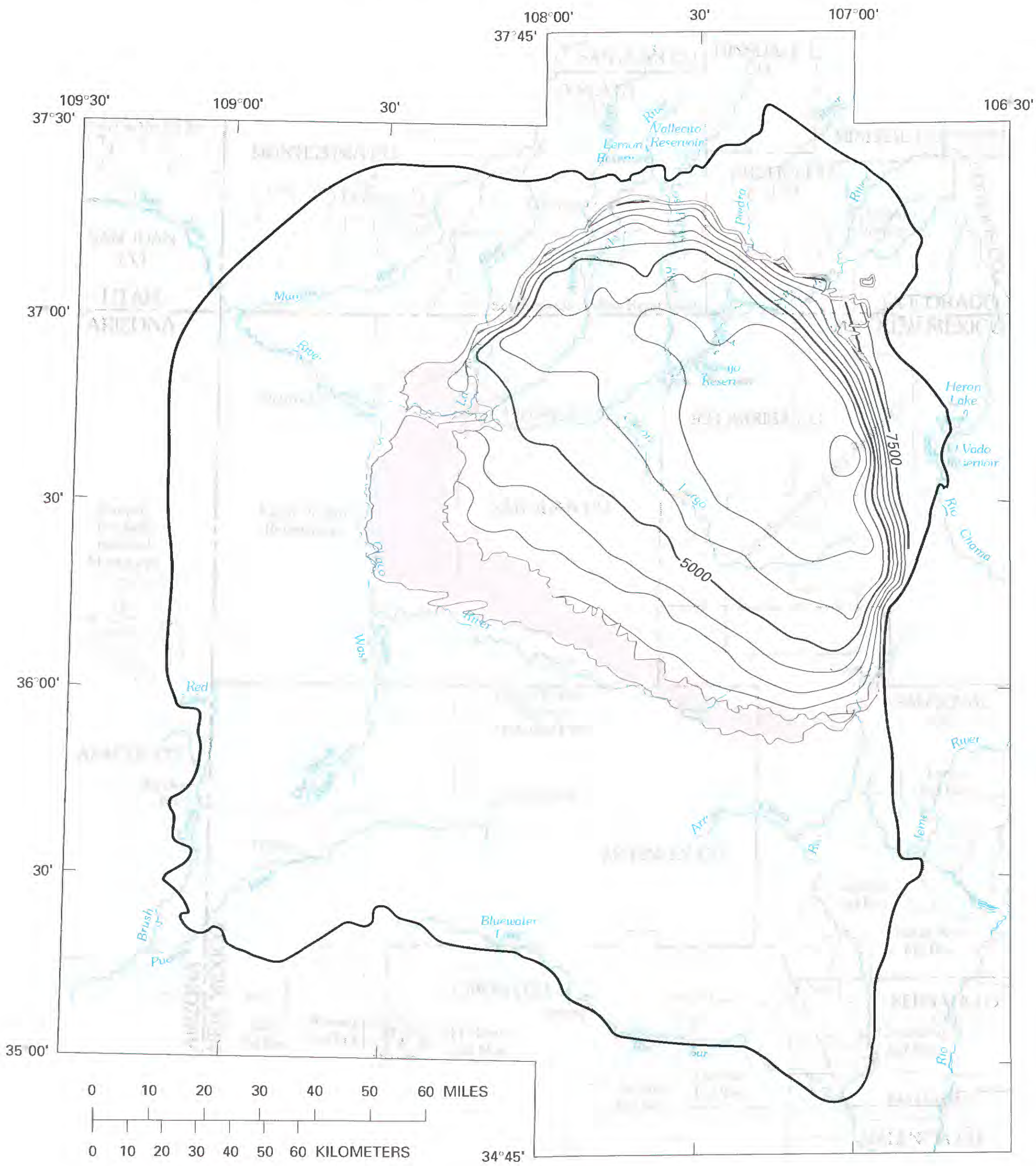
EXPLANATION

Outcrops of Kirtland Shale and Fruitland Formation, undivided—From Dane and Bachman (1965) and Tweto (1979)

Boundary of study area

—2000— **Unclipped and unannotated structure contour**—Shows approximate altitude relative to sea level. Contour interval 500 feet

FIGURE 33.—Unclipped and unannotated Geographic Information System line coverage of contours representing approximate altitude and configuration of the top of the combined Fruitland Formation and Kirtland Shale in theSan Juan study area.



EXPLANATION

Outcrops of Kirtland Shale and Fruitland Formation, undivided—From Dane and Bachman (1965) and Tweto (1979)

Boundary of study area

5000 **Clipped and annotated structure contour**—Shows approximate altitude relative to sea level. Contour interval 500 feet

FIGURE 34.—Clipped and annotated Geographic Information System coverage of the approximate altitude and configuration of the top of the combined Fruitland Formation and Kirtland Shale in the San Juan Basin study area. Modified from Kernodle and others (1990).

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