Geologic Framework of Pre-Cretaceous Rocks in the Southern Ute Indian Reservation and Adjacent Areas, Southwestern Colorado and Northwestern New Mexico

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COVER PHOTOGRAPH—Chief Buckskin Charley (circa 1840–1936) was the last hereditary chief of the Utes. He was named Chief of the Utes at the request of Chief Ouray, under whom he had served as sub-chief for many years. He is wearing an 1890 Benjamin Harrison peace medal, which was the last medal designed specifically for presentation to Indians. The photograph is from the Lisle Updyke Photo-Collection of Dr. Robert W. Delany and is reprinted by permission of Dr. Robert W. Delany and Jan Pettit.

Geologic Framework of Pre-Cretaceous Rocks in the Southern Ute Indian Reservation and Adjacent Areas, Southwestern Colorado and Northwestern New Mexico

By STEVEN M. CONDON

GEOLOGY AND MINERAL RESOURCES OF THE
SOUTHERN UTE INDIAN RESERVATION

Edited by ROBERT S. ZECH

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1505-A

*Prepared in cooperation with the
Southern Ute Tribe and the
U.S. Bureau of Indian Affairs*

*Stratigraphy and structure of
Precambrian to Jurassic rocks of the
Southern Ute Indian Reservation and
adjacent areas*

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PREFACE

At the request of the Southern Ute Tribe and the Energy and Mineral Division of the U.S. Bureau of Indian Affairs, the U.S. Geological Survey began a program in 1984 to study the geology and mineral resources of the Southern Ute Indian Reservation. The objective is to develop a series of investigations that characterize the geology and structure of the Reservation and that address a variety of resource-related problems. The boundary of the area covered by each investigation is determined by the nature of the specific investigation and accordingly may include only topical areas within the Reservation or the entire Reservation and adjacent areas.

The U.S. Geological Survey received valuable information and contributions from the Southern Ute Energy Department, without which these investigations would not have been possible. The final interpretive results of each investigation are presented as chapters of U.S. Geological Survey Professional Paper 1505. The chapters will be published as the interpretive products of the investigations become available.

Robert S. Zech
Editor

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Edited by ROBERT S. ZECH

GEOLOGIC FRAMEWORK OF PRE-CRETACEOUS ROCKS IN THE SOUTHERN UTE INDIAN RESERVATION AND ADJACENT AREAS, SOUTHWESTERN COLORADO AND NORTHWESTERN NEW MEXICO

By STEVEN M. CONDON

ABSTRACT

This report is a discussion and summary of Jurassic and older rocks in the Southern Ute Indian Reservation and adjacent areas, southwestern Colorado and northwestern New Mexico, and is based on analysis of geophysical logs and observations of outcrops. The Reservation, which is located in the northern San Juan Basin, has been the site of deposition of sediments for much of the Phanerozoic. Geologic times represented on the Reservation are the Precambrian, Cambrian, Devonian, Mississippian, Pennsylvanian, Permian, Triassic, Jurassic, Cretaceous, Tertiary, and Quaternary. Rocks of Ordovician and Silurian age have not been reported in this region.

Thicknesses of pre-Cretaceous sedimentary rocks range from about 750 feet (229 meters) on the Archuleta arch, east of the Reservation, to more than 8,300 feet (2,530 meters) just northwest of the Reservation. About 5,500 feet (1,676 meters) of pre-Cretaceous sedimentary rocks occur in the central part of the Reservation, near Ignacio. At Ignacio the top of the Jurassic lies at a depth of 7,600 feet (2,316 meters) below the surface, which is composed of Tertiary rocks. As much as 2,500 feet (762 meters) of Tertiary rocks occur in the area. More than 10,000 feet (3,048 meters) of Cretaceous and younger rocks, and 15,600 feet (4,755 meters) of all Phanerozoic sedimentary rocks occur in the vicinity of the Reservation.

In the early Paleozoic the area that includes the Southern Ute Reservation was on the stable western shelf of the craton. During this time sediments that compose the following shallow-marine clastic and carbonate rocks were deposited: the Upper Cambrian Ignacio Quartzite (0–150 feet; 0–46 meters), Upper Devonian Elbert Formation (50–200 feet; 15–61 meters), Upper Devonian Ouray Limestone (10–75 feet; 3–23 meters), and Mississippian Leadville Limestone (0–250 feet; 0–76 meters).

Mixed carbonate and clastic deposition, which was punctuated by a unique episode of deposition of evaporite sediments, continued through the Pennsylvanian after a significant episode of erosion at the end of the Mississippian. Pennsylvanian rocks on the Reservation are the Molas Formation (20–100 feet; 6–30 meters) and Hermosa Group (400–2,800 feet; 122–853 meters), which consists of the Pinkerton Trail Formation (40–120 feet; 12–36 meters), Paradox Formation and equivalent rocks (200–1,800 feet; 61–549 meters), and Honaker Trail Formation (200–1,300 feet; 61–396 meters). A unit that is transitional between the Pennsylvanian and Permian is the Rico Formation, which is about 200 feet (61 meters) thick across most of the Reservation area.

The close of the Paleozoic Era was marked by a great influx of arkosic clastic sediments from uplifted highlands to the north of the Reservation area during the Permian. Near the paleomountain front the Cutler Formation (presently as thick as 8,000 feet; 2,438 meters) formed as a result of deposition of arkosic sediments; however, the original thickness of the Cutler is unknown due to an unconformity at its top. In the area of the Reservation the Cutler has group status and has been divided into several formations: the Halgaito Formation (350–800 feet; 107–244 meters), Cedar Mesa Sandstone and equivalent rocks (150–350 feet; 46–107 meters), Organ Rock Formation (500–900 feet; 152–274 meters), and De Chelly Sandstone (0–100 feet; 0–30 meters). The sediments of these formations were deposited in a variety of environments, including eolian, mud-flat, and fluvial systems.

Following an episode of erosion in the Early and Middle(?) Triassic, deposition in the area of the Southern Ute Reservation continued during the Mesozoic. Sediments of the Upper Triassic Dolores and correlative Chinle Formations were deposited in fluvial, lacustrine, and minor eolian environments. On the Reservation the Dolores is 500–1,200 feet (152–366 meters) thick. Lower Jurassic eolian and fluvial deposits may have been present in much of the Reservation area but have been removed almost entirely. Only a thin remnant of the Wingate Sandstone (0–50 feet; 0–15 meters) of the Glen Canyon Group is left on the extreme western side of the Reservation.

Deposition continued during the Middle and Upper Jurassic, first in marginal-marine environments and then in eolian, fluvial, and

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lacustrine environments. Rocks of this time interval are the Entrada Sandstone (100–200 feet; 30–61 meters), Wanakah Formation (120–280 feet; 36–85 meters), Junction Creek Sandstone and equivalent rocks (0–300 feet; 0–91 meters), and Morrison Formation (450–500 feet; 137–152 meters). The Wanakah Formation is divided into the basal Todilto Limestone Member and equivalent rocks (10–120 feet; 3–36 meters), Beclabito Member and equivalent rocks (75–100 feet; 23–30 meters), and Horse Mesa Member and equivalent rocks (40–60 feet; 12–18 meters). The Morrison is divided into the Salt Wash Member (50–150 feet; 15–46 meters), Recapture Member (0–100 feet; 0–30 meters), Westwater Canyon Member (0–200 feet; 0–61 meters), and Brushy Basin Member (150–300 feet; 46–91 meters).

The present structural setting of the Southern Ute Reservation in the northern San Juan Basin wasn't established until after deposition of the Morrison Formation. The Laramide orogeny, which occurred in Late Cretaceous to Eocene time, reactivated older tectonic elements and formed new elements to give the northern basin its present configuration.

INTRODUCTION

The Southern Ute Indian Reservation is located in southwestern Colorado, in the northern San Juan Basin (fig. 1), on the eastern side of the Colorado Plateau. The Reservation occupies a strip of land 15 mi (24 km) wide by 73 mi (117 km) long (Boyce and Burch, 1988, p. 13). The Reservation is within what is commonly called the Four Corners area, so named because the area is near the point where Colorado, Utah, Arizona, and New Mexico meet. The topography of the Reservation varies from canyons and mesas in the Bridge Timber Mountain, Mesa Mountains, and H–D Hills areas to subdued hills in the central part of the Reservation. Much of the eastern part of the Reservation is heavily forested and sparsely populated and contains few access roads. Boyce and Burch (1988) provided detailed information on the history and demographics of the Southern Ute Reservation and Tribe.

The Southern Ute Reservation is mainly in the northern part of the structural and sedimentary San Juan Basin, just north of the deepest part of the basin (fig. 2; Thaden and Zech, 1984). The present structure of the area was largely shaped by Laramide (Late Cretaceous through Eocene) and later tectonic activity (Tweto, 1975; Woodward and Callender, 1977, p. 212). The area was also on the edge of the older Paleozoic Paradox basin during deposition of the sediments of the Pennsylvanian Hermosa Group and the Permian Cutler Group.

Figure 2 shows various structural elements in southwestern Colorado and northwestern New Mexico, using the terminology of Kelley and Clinton (1960). The contours, which are drawn on the top of the Jurassic Morrison Formation, show the effects of Laramide deformation. Faults have not been shown on this figure because the amount of offset on known faults is not significant at this scale; plate 1 shows faults in this region in detail. The central part of the San Juan Basin (8) is flanked on the west by the Hogback monocline (1) and on the east by the Archuleta arch (7). The monoclinal rim extends unbroken around the north side of the basin, just south of Durango and just north of Bayfield.

A structural bench, the Four Corners platform (2), lies between the San Juan Basin and the Blanding basin (4). The Upper Cretaceous to Tertiary laccolithic intrusions of Ute dome (3) and La Plata dome (5) are evident. The northern rim of the San Juan Basin is defined by the uplift of the San Juan dome (6). The Chama basin (9) and the San Juan sag (10) are low structural features on the east and northeast sides, respectively, of the Archuleta arch (7).

Rocks of the Cambrian, Devonian, Mississippian, Pennsylvanian, Permian, Triassic, Jurassic, Cretaceous, and Tertiary Systems are present at the surface or in the subsurface of the Reservation (fig. 3). Post-Cambrian erosion or nondeposition removed any Ordovician or Silurian rocks that may have been present. Upper Cretaceous through lower Tertiary rocks crop out on the Reservation; older units are exposed in uplifts and canyons west and north of the Reservation. A major obstacle to the study of older sedimentary rocks is the lack of deep drill holes on most of the Reservation; only 11 wells penetrate below the Cretaceous within the boundaries of the Reservation. Most of the deep drill holes are on the Four Corners platform on the far west side of the Reservation in the Red Mesa area. In addition, one hole, the Stanolind No. 6–B Ute Indian, penetrates basement in the central part of the Reservation, south of Ignacio (fig. 1).

This report is a brief review of the rock units of Jurassic and older ages that are present in the subsurface of the Southern Ute Reservation (fig. 3, pl. 1). Information on each rock unit, such as lithology, thickness, distribution, and environment of deposition is presented, together with references to more detailed work by others. Isopach maps illustrate the thickness and distribution of subsurface units, but cover a much larger area than just the Reservation. The area of the Reservation is placed in a larger, regional context so that thickness trends of rock units on the Reservation, especially in the eastern part where data are scarce, would be more apparent.

A knowledge of the general lithology and distribution of pre-Cretaceous rocks is important because some units are oil and gas producers on the Four Corners platform (Fassett, 1978a, b, 1983; Huff-

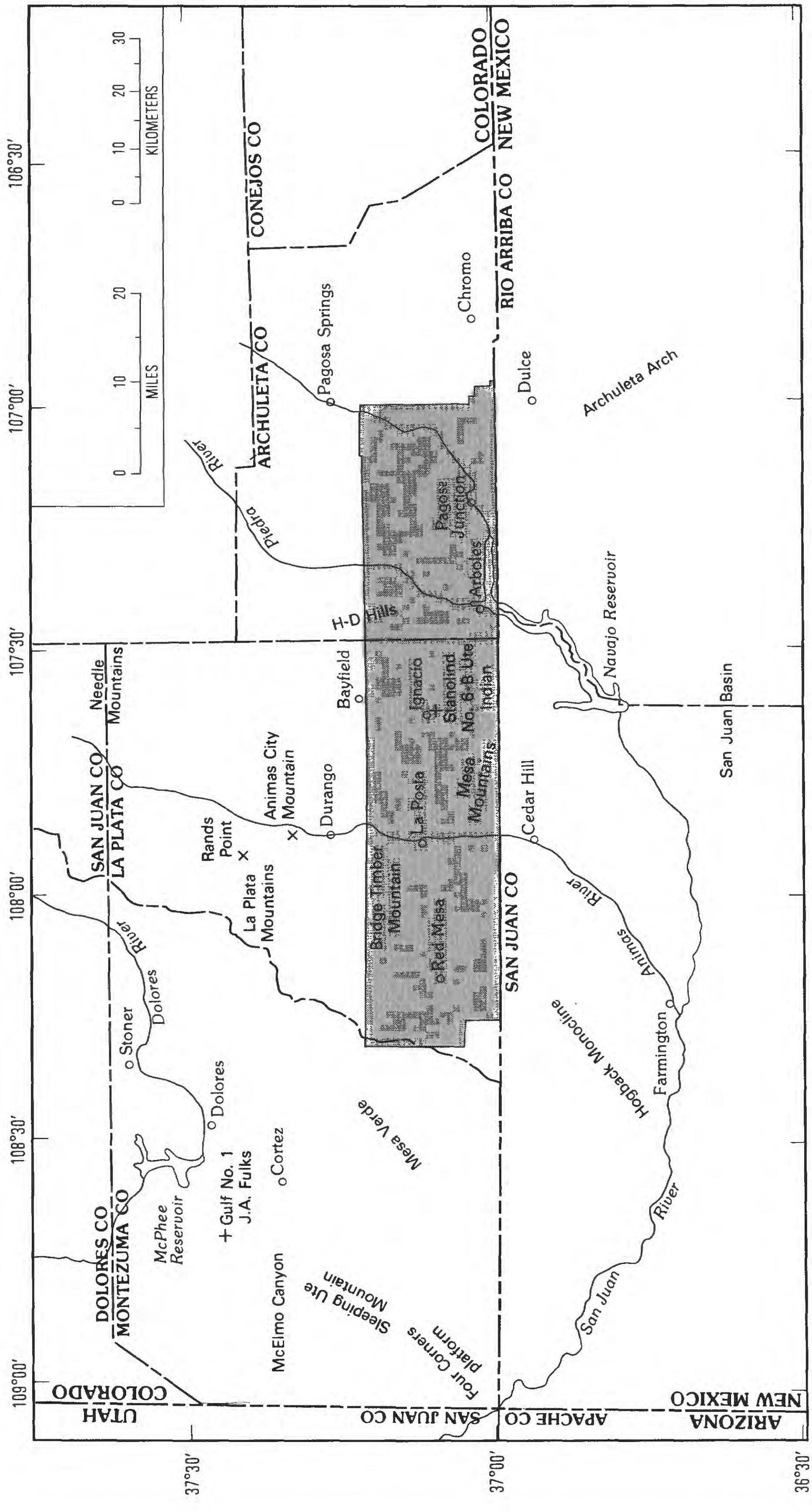

FIGURE 1.—Index map of the Southern Ute Indian Reservation (pattern) and adjacent areas.

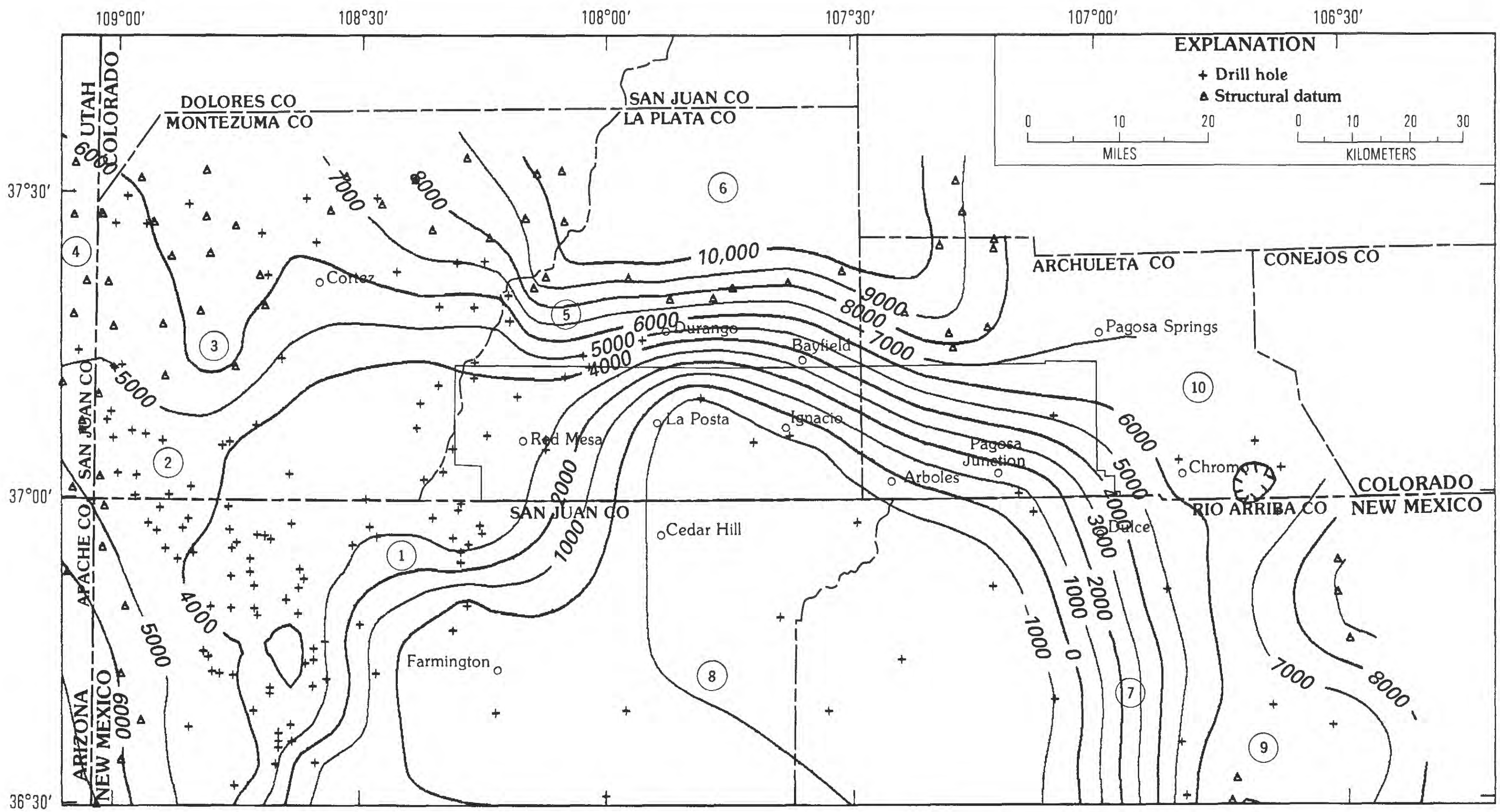

FIGURE 2.—Structure contour map drawn on the top of the Jurassic Morrison Formation (modified from unpublished data, A.C. Huffman, Jr., and S.M. Condon, 1990). Contour interval is 1,000 feet. Datum is mean sea level. Circled numbers on the figure refer to the following structural elements: (1) Hogback monocline, (2) Four Corners platform, (3) Ute dome, (4) Blanding basin, (5) La Plata dome, (6) San Juan dome, (7) Archuleta arch, (8) central San Juan Basin, (9) Chama basin, (10) San Juan sag. Names of structural elements from Kelley and Clinton (1960).

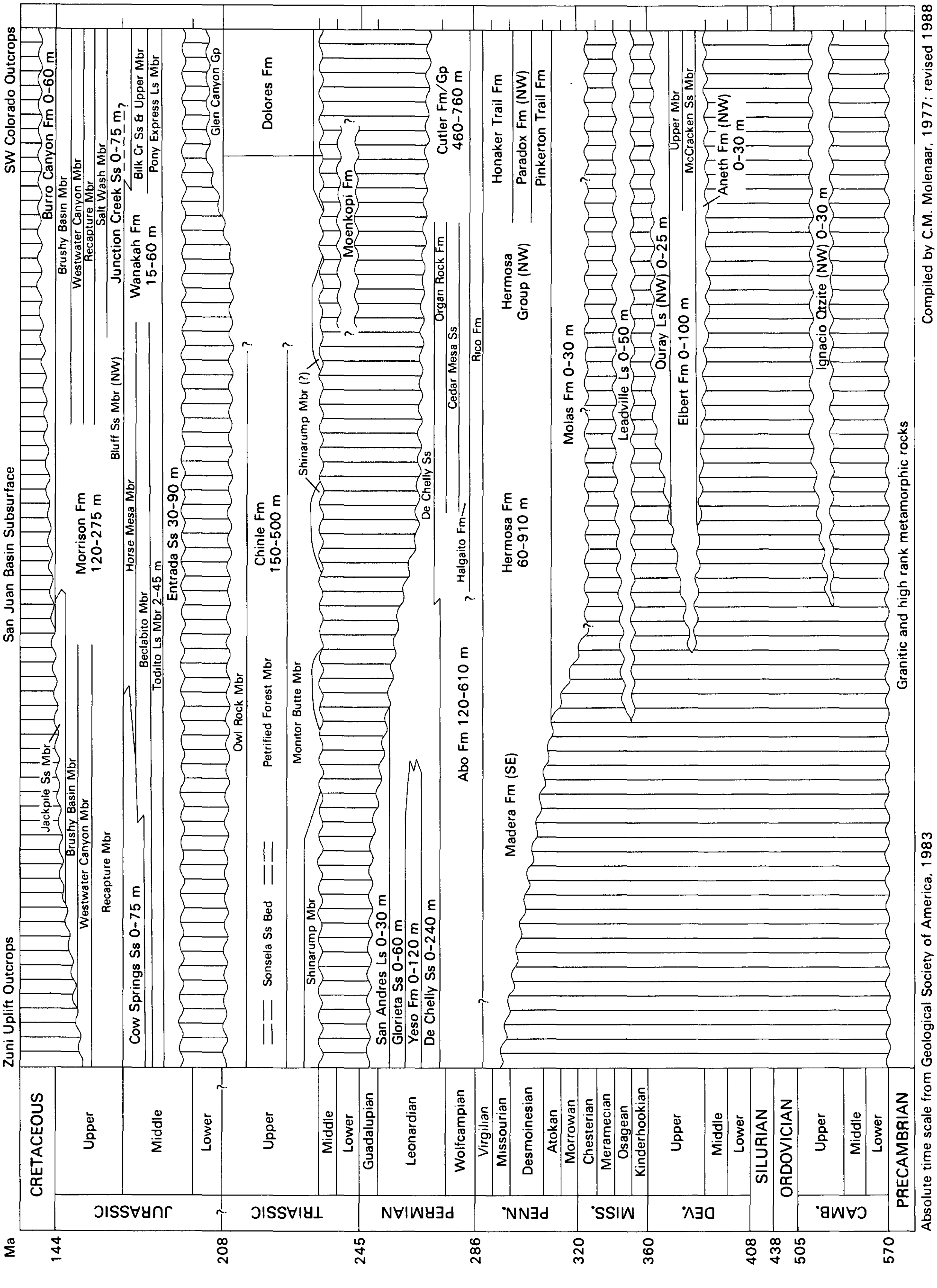

FIGURE 3.—Time-stratigraphic chart of stratigraphic units on the Southern Ute Indian Reservation and adjacent areas (modified from Molenaar, 1989).

man, 1987; Peterson and others, 1965). Other pre-Cretaceous rocks have been proposed for or are already used as waste-water injection repositories for gas wells on the Reservation (Zimpfer and others, 1988). Although Cretaceous rocks are an important source of gas and coal in the northern San Juan Basin, Cretaceous and Tertiary sedimentary rocks are not discussed here because they are the subject of other reports in this series.

Acknowledgments.—Thanks are extended to R.C. Johnson, J.E. Fassett, A.C. Huffman, Jr., K.J. Franczyk, and C.A. Sandberg for critically reviewing this report. Special thanks are due to Curt Huffman for his efforts in our cooperative study of pre-Cretaceous rocks throughout the San Juan Basin and vicinity. The present report is a small part of that larger endeavor.

PREVIOUS INVESTIGATIONS

No previous studies of pre-Cretaceous rocks have been made exclusively on Reservation land because of the lack of outcrops of those units and the sparsity of subsurface control there. However, numerous regional studies that include all or part of the Reservation are cited here. Many other topical papers concerned with this area are contained in various guidebooks of the Rocky Mountain Association of Geologists, the Four Corners Geological Society, the Intermountain Association of Petroleum Geologists, and the New Mexico Geological Society. Finch and others (1989) and Fassett (1988) also summarized the geology of the Reservation and surrounding areas.

Studies concerned mainly with lower Paleozoic rocks (Mississippian and older) are: Armstrong and Holcomb (1989), Armstrong and others (1980), Baars and Campbell (1968), Baars and Knight (1957), Baars and See (1968), Parker and Roberts (1966), Rhodes and Fisher (1957), Sandberg and others (1989), and Stevenson and Baars (1977).

Studies of Pennsylvanian and Permian rocks are: Baars (1962), Baars and Stevenson (1977), Campbell (1979, 1980, 1981), Fetzner (1960), Girdley (1968), Jentgen (1977), Merrill and Winar (1958), Pratt (1968), Stevenson and Baars (1986), Wengerd and Matheny (1958), and Wengerd and Strickland (1954).

Studies of Triassic and Jurassic rocks are: Baker and others (1936, 1947), Blodgett (1984), Condon and Huffman (1984, 1988), Condon and Peterson (1986), Craig and others (1955, 1959), Ekren and Houser (1965), Goldman and Spencer (1941), O'Sullivan (1977), Stewart and others (1972), Turner-Peterson (1985), Turner-Peterson and Fishman (1986), and Wright and others (1962).

Reports that summarize the entire stratigraphic section are: Baars and Ellingson (1984), Cross and Purington (1899), Cross and Spencer (1900), Cross and others (1905), Eckel (1949), Peterson and others (1965), and Read and others (1949).

METHODS

The isopach maps in this report were compiled from a data base that consists of 206 geophysical logs and 28 published measured outcrop sections in Colorado, Utah, Arizona, and New Mexico (fig. 4). The tops of formations were picked from geophysical logs by S.M. Condon and A.C. Huffman, Jr., as part of a regional study of the San Juan Basin. The geographical boundaries used for the isopach and structure maps of this report were chosen arbitrarily; the object was to show the area of the Southern Ute Reservation in relation to surrounding areas that have more subsurface control. Additional structural control points (top of the Jurassic) were derived from geologic maps in order to tie surface and subsurface structure together.

To ensure that formation tops derived from geophysical logs were laterally consistent, several cross sections were constructed (A.C. Huffman, Jr., and S.M. Condon, unpublished data, 1990). Thickness data were then gridded and contoured using a Dynamic Graphics computer program called Interactive Surface Modeling (ISM). The grid spacing used to construct the isopach maps was 4 mi (6.4 km) in both the x and y directions; four data points were used to calculate values at each grid intersection point. The grid spacing for the structure contour map was 1.3 mi (2.1 km); four data points were also used to calculate each grid node for this map. The preliminary contour maps were then evaluated to resolve any problems with well-log picks and were regridded and recontoured as necessary. In some cases the contour lines were smoothed by hand in small areas to even out the computer-generated lines. These maps are small portions of maps that cover the much larger area of the San Juan Basin. Although some of the contour lines on the maps of this report may appear to be uncontrolled by data at the map margins, in most cases control points were used that fell just outside the map boundaries.

Because depths of drill holes varied, isopach and structure contour maps for deeper rock units were constructed from fewer than the total number of 206 holes in the data set that are shown on figure 4. The holes used for each map are plotted on the individual maps; the structural control points taken from geologic maps are also shown on the structure contour map.

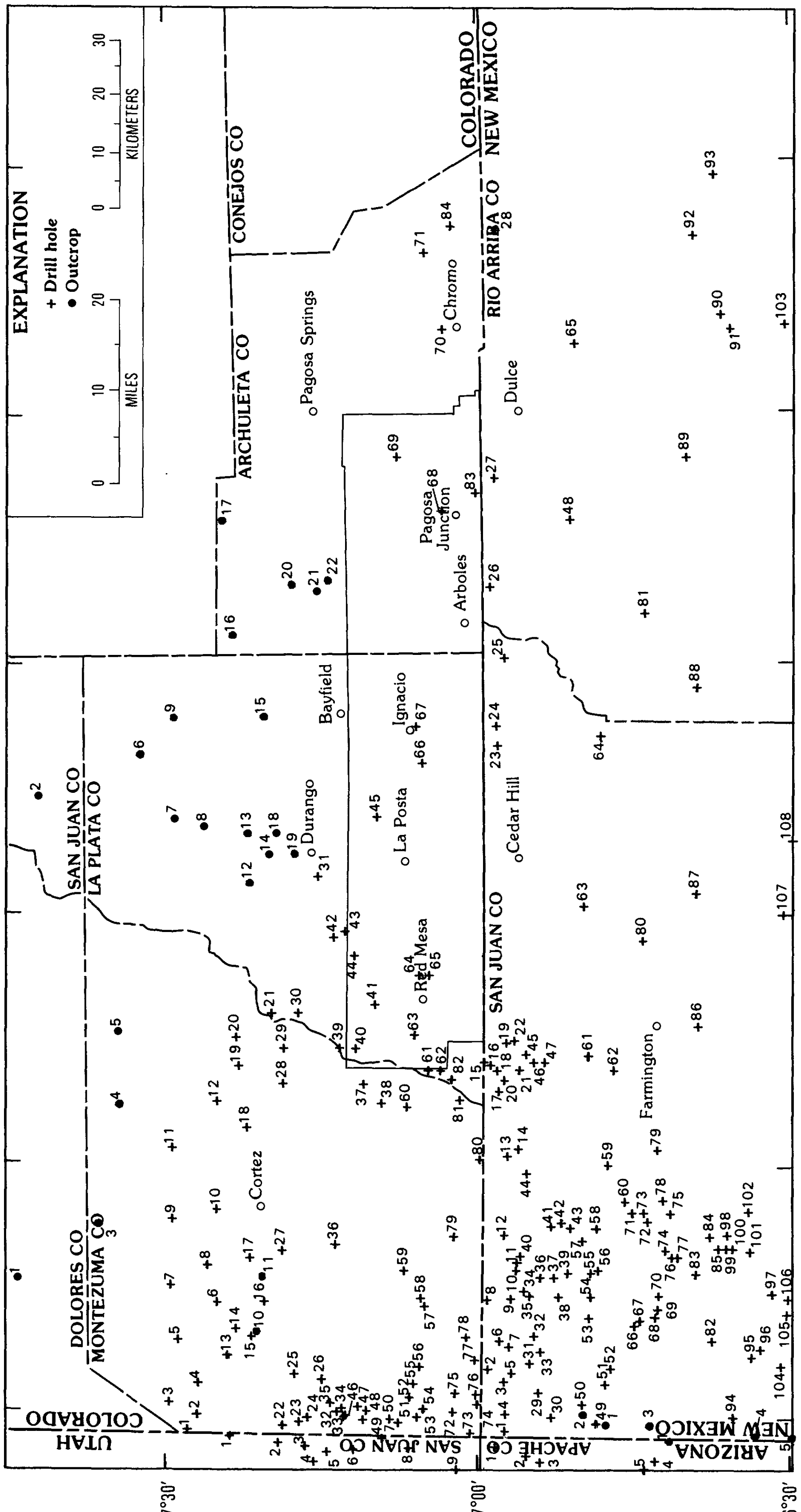

FIGURE 4.—Map showing location of drill holes and outcrop measured sections that were used to construct the isopach maps and structure contour map.

The lack of data in the central and eastern parts of the Reservation makes projections of thickness trends in those areas speculative. Table 1 lists the drill holes (grouped by state) that were used to construct the isopach maps and structure contour map in this report.

Jurassic and older rocks are exposed at the surface north and west of the Reservation, and after reviewing the available geological literature on outcrops in those areas, reconnaissance field studies were conducted for this report. Interpretation of data from these outcrops, for example, data on lithology and environment of deposition, resulted in improved interpretation of the units in the subsurface of the Reservation. The geological literature of this region also provided many thickness values for exposed rocks. Table 2 lists the measured sections that were used as data points for the isopach maps and includes references for the sections.

STRATIGRAPHY

PRECAMBRIAN CRYSTALLINE AND METAMORPHIC ROCKS

Crystalline rocks that underlie the Southern Ute Reservation are of Precambrian age. Precambrian rocks have been penetrated by only a few drill holes in the Four Corners area, and lithologic logs that are available for the deep holes record granite as the lithology of the Precambrian rocks. Zabel (1955, p. 135) noted that biotite-hornblende granite was drilled in the Gulf No. 1, J.A. Fulks well (sec. 27, T. 37 N., R. 17 W., Montezuma County, Colo.) (fig. 1).

The following descriptions and interpretations of the Precambrian sequence in the Durango area are derived from Baars and Ellingson (1984) and Tewksbury (1981, 1985). Ages of rocks discussed here are drawn from Tewksbury (1985); slightly different ages were presented by Baars and Ellingson (1984). The above reports also summarize previous alternative interpretations of the Precambrian rocks of this area.

Proterozoic Precambrian rocks are exposed in a broad area north of the Reservation in an area centering on the Needle Mountains (fig. 1). The oldest Precambrian rocks in the western part of the area (Animas River valley) are composed of gneiss, schist, and amphibolite, of unknown age, that had previously been correlated with the Early Proterozoic Irving Formation of the eastern Needle Mountains (Baars and Ellingson, 1984, p. 8). Intrusive and volcanic rocks of the Early Proterozoic Twilight Gneiss were emplaced into and on top of the gneiss, schist, and amphibolite about 1,760 Ma (Tewksbury, 1985, p. 226). The Uncompahgre Formation, of Early and Middle Proterozoic age, is in fault contact with both the gneiss, schist, and amphibolite and the Twilight Gneiss (Tewksbury, 1985, p. 227). The 1,680–1,640-Ma Ten-mile Granite, 1,675-Ma Bakers Bridge Granite, 1,420-Ma Electra Lake Gabbro, and 1,320-Ma Trimble Granite intruded the older Precambrian rocks.

In the eastern Needle Mountains the Proterozoic sequence consists of the Vallecito Conglomerate (Early Proterozoic), the overlying Irving Formation and metaconglomerate of Middle Mountain, the Uncompahgre Formation, and the 1,430-Ma Eolus Granite (Baars and Ellingson, 1984, p. 10). Tewksbury (1985, p. 226) interpreted the Irving Formation and the Twilight Gneiss as coeval deposits; however, Baars and Ellingson (1984, p. 10) stated that the Vallecito Conglomerate, Irving Formation, and metaconglomerate of Middle Mountain are all younger than the Twilight Gneiss. The allochthonous Uncompahgre Formation is also present in the eastern Needle Mountains, and was faulted onto other, older Precambrian rocks in this area (Tewksbury, 1985, p. 224). The Uncompahgre crops out mainly in the Needle Mountains, but small exposures are present in the Piedra River canyon (fig. 1, pl. 1). The Uncompahgre itself was deformed and metamorphosed prior to emplacement and intrusion of the 1,430-Ma Eolus Granite (Tewksbury, 1985, p. 226), which is also exposed in the Needle Mountains and Piedra River areas (pl. 1). The distribution of these different rock types beneath the Southern Ute Reservation is unknown.

An irregular, unconformable erosion surface developed on exposed Precambrian rocks before deposition of any Phanerozoic sediments. This basement topography affected the distribution and thickness of some of the lower Paleozoic rocks, which makes correlation of these units from surface exposures to the subsurface difficult. Additionally, postdepositional structural movement created a series of northwest-trending horsts and grabens in which units were selectively eroded or preserved (Stevenson and Baars, 1977, 1986).

CAMBRIAN ROCKS

IGNACIO QUARTZITE

The Upper Cambrian Ignacio Quartzite, which was named by Cross and others (1905, p. 3), is the oldest Phanerozoic sedimentary rock and only Cambrian unit in this area (fig. 3). In exposures in the Animas River valley north of Durango and in the Piedra River canyon

TABLE 1.—*Number, location, operator, and well name of geophysical logs used in this report*

No.	Location	Operator and well name	County
Utah:			
1	Sec. 15, T. 39 S., R. 26 E.	Mobil Oil Corp., No. 1 Federal GG	San Juan.
2	Sec. 9, T. 40 S., R. 26 E.	Shell Oil Co., No. 2 Hovenweep	San Juan.
3	Sec. 28, T. 40 S., R. 26 E.	Pure Oil Co., No. 28–B3 E. Aneth	San Juan.
4	Sec. 31, T. 40 S., R. 26 E.	Monsanto Co., Navajo A–4	San Juan.
5	Sec. 8, T. 41 S., R. 26 E.	Kimbark Exploration Co. & Zoller & Danneberg, Mail Trail Mesa No. 1.	San Juan.
6	Sec. 28, T. 41 S., R. 26 E.	Superior Oil Co., No. 1–28 Navajo	San Juan.
7	Sec. 10, T. 42 S., R. 26 E.	R.G. Boekel, Navajo No. 32–10	San Juan.
8	Sec. 28, T. 42 S., R. 26 E.	Tiger Oil Co. & Davis Oil Co., Navajo No. 1	San Juan.
9	Sec. 19, T. 43 S., R. 26 E.	Davis Oil Co. & Tiger Drilling Co., No. 1–E Navajo	San Juan.
Colorado:			
1	Sec. 15, T. 37 N., R. 20 W.	Big Horn Powder River, No. 1–A Govt.	Montezuma.
2	Sec. 24, T. 37 N., R. 20 W.	Texota Oil-Ambassador Oil, No. 1–B Colorado-Federal	Montezuma.
3	Sec. 6, T. 37 N., R. 19 W.	Mobil Oil Corp., No. 1 Federal–II	Montezuma.
4	Sec. 21, T. 37 N., R. 19 W.	Pan American Petroleum Corp., No. 1 Fehr	Montezuma.
5	Sec. 8, T. 37 N., R. 18 W.	Calvert Drilling Inc., No. 1 Woods Canyon	Montezuma.
6	Sec. 36, T. 37 N., R. 18 W.	Shell Oil Co., Federal 36–37–18 No. 1	Montezuma.
7	Sec. 5, T. 37 N., R. 17 W.	Harbor Oil & Gas–J.R. Brown, No. 1 Reed	Montezuma.
8	Sec. 27, T. 37 N., R. 17 W.	Gulf Oil Co., No. 1 Fulks	Montezuma.
9	Sec. 4, T. 37 N., R. 16 W.	Shell Oil Co., State 4–37–16 No. 1	Montezuma.
10	Sec. 34, T. 37 N., R. 16 W.	Fundamental Oil Co., Elliot No. 1–34	Montezuma.
11	Sec. 2, T. 37 N., R. 15 W.	Read and Stevens, Inc., Shenandoah-Veach No. 1	Montezuma.
12	Sec. 34, T. 37 N., R. 14 W.	Davis Oil Co., Bayles No. 1	Montezuma.
13	Sec. 1, T. 36 N., R. 19 W.	Pan American Petroleum Corp., USA Pan Am 'B' No. 1	Montezuma
14	Sec. 9, T. 36 N., R. 18 W.	Shell Oil Co., Federal 9–36–18 No. 1	Montezuma.
15	Sec. 20, T. 36 N., R. 18 W.	Great Western Drilling Co., No. 1 W. McElmo-Govt.	Montezuma
16	Sec. 25, T. 36 N., R. 18 W.	Byrd-Frost, No. 1 MacIntosh	Montezuma.
17	Sec. 23, T. 36 N., R. 17 W.	Shell Oil Co., Federal 23–36–17 No. 1	Montezuma.
18	Sec. 18, T. 36 N., R. 14 W.	Reynolds Mining, No. 1 Point Lookout	Montezuma.
19	Sec. 8, T. 36 N., R. 13 W.	Walter Duncan, Culp No. 1	Montezuma.
20	Sec. 11, T. 36 N., R. 13 W.	Arapahoe Drilling Co., Arapahoe Reddert No. 1	Montezuma.
21	Sec. 32, T. 36 N., R. 12 W.	Davis Oil Co., Peaker Federal No. 1	La Plata.
22	Sec. 3, T. 35 N., R. 20 W.	Tom Vessels Jr., Vessels No. 1	Montezuma.
23	Sec. 14, T. 35 N., R. 20 W.	Kimbark Exploration Co. & Alpine Oil Co., Govt. Flodine No. 1.	Montezuma.
24	Sec. 25, T. 35 N., R. 20 W.	Monsanto Co., Duncan No. 1	Montezuma.
25	Sec. 15, T. 35 N., R. 19 W.	Michael P. Grace, Federal No. 1	Montezuma.
26	Sec. 33, T. 35 N., R. 19 W.	The Texas Company, No. 1–A Jones-Federal	Montezuma.
27	Sec. 1, T. 35 N., R. 17 W.	George M. Hill National Drilling Co., No. 1 McCabe	Montezuma.
28	Sec. 1, T. 35 N., R. 14 W.	Slick-Moorman Oil Co., No. 1 C.J. Weber	Montezuma.
29	Sec. 3, T. 35 N., R. 13 W.	Davis Oil Co., Elliott Federal No. 1	Montezuma.
30	Sec. 17, T. 35 N., R. 12 W.	Miller & Shelly, Karl Hauert No. 1	La Plata.
31	Sec. 26, T. 35 N., R. 10 W.	Cayman Corp., Colorado Federal No. 1	La Plata.
32	Sec. 1, T. 34 N., R. 20 W.	Pan American Petroleum Corp., Ute Mountain Tribal 'J' No. 2.	Montezuma.
33	Sec. 11, T. 34 N., R. 20 W.	Phillips Petroleum Co., No. 2 Desert Canyon	Montezuma.
34	Sec. 12, T. 34 N., R. 20 W.	Vaughey & Vaughey, No. 1–A Ute	Montezuma.
35	Sec. 6, T. 34 N., R. 19 W.	Atlantic Richfield Co., West Ute Mountain No 1	Montezuma.
36	Sec. 1, T. 34 N., R. 17 W.	National Drilling Co., Higgins No. 1	Montezuma.
37	Sec. 24, T. 34 N., R. 14 W.	Houston Oil & Minerals Corp., Ute Mountain Federal No. 14–24.	Montezuma.
38	Sec. 34, T. 34 N., R. 14 W.	Houston Oil and Minerals Corp., Ute Mounatin No. 44–34	Montezuma.
39	Sec. 3, T. 34 N., R. 13 W.	Davis Oil Co., Menefee Federal No. 1	La Plata.
40	Sec. 15, T. 34 N., R. 13 W.	Cities Service Oil Co., Story A No. 1	La Plata.
41	Sec. 28, T. 34 N., R. 12 W.	General Petroleum Corp., No. 44–28 Butler	La Plata.
42	Sec. 3, T. 34 N., R. 11 W.	Great Western Drilling Co., Ft. Lewis School Land No. 1.	La Plata.
43	Sec. 11, T. 34 N., R. 11 W.	Texaco Inc., State 'O' No. 1	La Plata.
44	Sec. 17, T. 34 N., R. 11 W.	General Petroleum Corp., No. 55–17 Kikel	La Plata.

TABLE 1.—*Number, location, operator, and well name of geophysical logs used in this report*—Continued

No.	Location	Operator and well name	County
Colorado—Continued			
45	Sec. 22, T. 34 N., R. 9 W.	Byrd Oil Corp., No. 1 Steve Simon 'A'	La Plata.
46	Sec. 3, T. 33½ N., R. 20 W.	The California Co., No. 5 Calco Superior Ute	Montezuma.
47	Sec. 11, T. 33½ N., R. 20 W.	Walter Duncan, Calco Superior Ute No. 1	Montezuma.
48	Sec. 14, T. 33½ N., R. 20 W.	Walter Duncan, Ute No. 1–14	Montezuma.
49	Sec. 15, T. 33½ N., R. 20 W.	Chevron Oil Co., Chevron Ute Tribal No. 9 (11–15)	Montezuma.
50	Sec. 34, T. 33½ N., R. 20 W.	Pure Oil Co., No. 1 Ute Tribal	Montezuma.
51	Sec. 4, T. 33 N., R. 20 W.	Forest Oil Corp., Ute 4–1	Montezuma.
52	Sec. 13, T. 33 N., R. 20 W.	Rocket Drilling Co., No. 1–D Ute	Montezuma.
53	Sec. 15, T. 33 N., R. 20 W.	Continental Oil Co., No. 3	Montezuma.
54	Sec. 23, T. 33 N., R. 20 W.	Signal Exploration Inc. et al., Marianna Springs-Ute Gov't. No. 1.	Montezuma.
55	Sec. 17, T. 33 N., R. 19 W.	Texaco, Inc., Ute Mountain Tribal B No. 1	Montezuma.
56	Sec. 22, T. 33 N., R. 19 W.	The California Co., No. 1 Ute Tribal	Montezuma.
57	Sec. 22, T. 33 N., R. 18 W.	The California Co., Ute Mountain Tribal No. 1	Montezuma.
58	Sec. 23, T. 33 N., R. 18 W.	Wintershall Oil & Gas Corp., Ute Mountain Tribal 23–32 Nighthawk.	Montezuma.
59	Sec. 9, T. 33 N., R. 17 W.	King Resources Co., Ute No. 1	Montezuma.
60	Sec. 8, T. 33 N., R. 14 W.	Tidewater Associated Oil Co., No. 1 Ute	Montezuma.
61	Sec. 24, T. 33 N., R. 14 W.	Norris Oil Co., Ute No. 1	La Plata.
62	Sec. 15, T. 33 N., R. 13 W.	Skelly Oil Co., No. 1 L.F. Benton	La Plata.
63	Sec. 14, T. 33 N., R. 12 W.	The Hathaway Co., No. 1 Barr	La Plata.
64	Sec. 23, T. 33 N., R. 12 W.	Davis Oil Co., Red Mesa Deep No. 1	La Plata.
65	Sec. 15, T. 33 N., R. 8 W.	Amoco Production Corp., Jessie Hahn No. 1	La Plata.
66	Sec. 17, T. 33 N., R. 7 W.	Stanolind Oil & Gas, No. 6–B Ute Indian	La Plata.
67	Sec. 32, T. 33 N., R. 3 W.	Sun Oil Co., J. Felix Gomer No. 1	Archuleta.
68	Sec. 5, T. 33 N., R. 2 W.	The Daube Co., Florance Newton No. 1	Archuleta.
69	Sec. 34, T. 33 N., R. 1 E.	Great Western Drilling Co., No. 1–A Simms	Archuleta.
70	Sec. 24, T. 33 N., R. 2 E.	William E. Hughes, Gramps No. 51	Archuleta.
71	Sec. 2, T. 32 N., R. 20 W.	Continental Oil Co., No. 4 Govt.	Montezuma.
72	Sec. 17, T. 32 N., R. 20 W.	Honolulu Oil Co., No. 1 Govt.	Montezuma.
73	Sec. 24, T. 32 N., R. 20 W.	Pan American Petroleum Corp., No. 1 Ute Mountain	Montezuma.
74	Sec. 7, T. 32 N., R. 19 W.	Continental Oil, Ute Mountain No. 1	Montezuma.
75	Sec. 19, T. 32 N., R. 19 W.	Continental Oil Co., No. 5 Ute Indian	Montezuma.
76	Sec. 23, T. 32 N., R. 19 W.	Rocket Drilling–Mohawk Petroleum, No. 1–C Ute	Montezuma.
77	Sec. 18, T. 32 N., R. 18 W.	Continental Oil Co., No. 2 Govt.	Montezuma.
78	Sec. 1, T. 32 N., R. 17 W.	Phillips-Mobil, Mesa 'A' No. 1	Montezuma.
79	Sec. 21, T. 32 N., R. 15 W.	Amerada Petroleum Corp., Ute Tribal No. 2	Montezuma.
80	Sec. 9, T. 32 N., R. 14 W.	El Paso Natural Gas Co., No. 9 Ute	La Plata.
81	Sec. 4, T. 32 N., R. 13½ W.	Knight and Miller Oil Corp., Aztec-Ute No. 1	La Plata.
82	Sec. 22, T. 32 N., R. 3 W.	Stanolind Oil & Gas Co., Southern Ute No. 1	Archuleta.
83	Sec. 2, T. 32 N., R. 3 E.	Wm. E. Hughes, J. Miller No. 1	Archuleta.
Arizona:			
1	Sec. 7, T. 41 N., R. 31 E.	Zoller & Danneberg, Navajo 161–1	Apache.
2	Sec. 36, T. 41 N., R. 30 E.	Texaco, Inc., No. 1–Z Navajo	Apache.
3	Sec. 2, T. 40 N., R. 30 E.	Depco, Inc., Midwest & Occidental, Navajo No. 1–2	Apache.
4	Sec. 12, T. 38 N., R. 30 E.	Pan American Petroleum Corp., Navajo Tribal AF No. 1.	Apache.
5	Sec. 2, T. 38 N., R. 30 E.	Depco, Inc., Navajo Tribal 4–2	Apache.
New Mexico:			
1	Sec. 26, T. 32 N., R. 21 W.	El Paso Natural Gas, No. 2 Bita Peak	San Juan.
2	Sec. 13, T. 32 N., R. 20 W.	Continental Oil Co., Navajo Tribal No. 1–13	San Juan.
3	Sec. 26, T. 32 N., R. 20 W.	Continental Oil Co., No. 1 Ute Mtn.	San Juan.
4	Sec. 30, T. 32 N., R. 20 W.	Humble Oil & Continental Oil, No. 3–B Navajo	San Juan.
5	Sec. 36, T. 32 N., R. 20 W.	Tenneco Oil Co., Navajo 590 No. 1	San Juan.
6	Sec. 21, T. 32 N., R. 19 W.	Continental Oil Co., No. 1–21 Navajo	San Juan.
7	Sec. 33, T. 32 N., R. 19 W.	Compass Exploration, Inc., Indian 1–33	San Juan.
8	Sec. 17, T. 32 N., R. 18 W.	The Texas Company, No. 1–N Navajo	San Juan.
9	Sec. 32, T. 32 N., R. 18 W.	Compass Exploration, Inc., 1–32 Navajo	San Juan.
10	Sec. 35, T. 32 N., R. 18 W.	Texaco, Inc., Navajo AJ No. 1	San Juan.

TABLE 1.—*Number, location, operator, and well name of geophysical logs used in this report*—Continued

No.	Location	Operator and well name	County
New Mexico—Continued			
11	Sec. 36, T. 32 N., R. 18 W.	Southern Union Gas Co., Navajo No. 1A	San Juan.
12	Sec. 28, T. 32 N., R. 17 W.	Texas Pacific Coal & Oil Co., No. 1–B Navajo	San Juan.
13	Sec. 25, T. 32 N., R. 16 W.	Cities Service Oil Co., Ute A No. 1	San Juan.
14	Sec. 31, T. 32 N., R. 15 W.	Forest Oil Co.-Kern County Land, et al., No. 1 Ute	San Juan.
15	Sec. 10, T. 32 N., R. 14 W.	El Paso–Delhi Oil Corp., No. 4 Delhi	San Juan.
16	Sec. 15, T. 32 N., R. 14 W.	El Paso Natural Gas Co., Ute No. 8	San Juan.
17	Sec. 19, T. 32 N., R. 14 W.	El Paso Natural Gas Co., No. 7 Ute	San Juan.
18	Sec. 21, T. 32 N., R. 14 W.	Southern Union Production Co., Barker No. 19.	San Juan.
19	Sec. 25, T. 32 N., R. 14 W.	Amoco Production Co., Mountain Ute Gas Com 'F' No. 1.	San Juan.
20	Sec. 29, T. 32 N., R. 14 W.	Aztec Oil & Gas Co., No. 13 Barker Dome	San Juan.
21	Sec. 33, T. 32 N., R. 14 W.	Pan American Petroleum Corp., Ute Mountain Tribal No. K–1.	San Juan.
22	Sec. 36, T. 32 N., R. 14 W.	Stanolind Oil & Gas, No. 4 Ute Indian	San Juan.
23	Sec. 10, T. 32 N., R. 8 W.	Southland Royalty Co., Reese Mesa No. 6	San Juan.
24	Sec. 12, T. 32 N., R. 8 W.	Aztec Oil & Gas Co., Reese Mesa No. 1	San Juan.
25	Sec. 17, T. 32 N., R. 6 W.	Amerada Petroleum Co., Allison Unit No. 1	San Juan.
26	Sec. 10, T. 32 N., R. 5 W.	Stanolind Oil & Gas Co., San Juan 32–5 Unit No. 3	Rio Arriba.
27	Sec. 23, T. 32 N., R. 3 W.	Pan American Petroleum Corp., Pagosa-Jicarilla No. 1	Rio Arriba.
28	Sec. 8, T. 32 N., R. 3 E.	Rhine Petroleum Industries, No. 2 Sargent	Rio Arriba.
29	Sec. 15, T. 31 N., R. 20 W.	British-American Oil Prod. Co., No. 1–E Navajo	San Juan.
30	Sec. 19, T. 31 N., R. 20 W.	Atlantic Richfield Co., No. 1 Chevron-Ladd	San Juan.
31	Sec. 7, T. 31 N., R. 19 W.	Monsanto Chemical Co., Natoni No. 1	San Juan.
32	Sec. 10, T. 31 N., R. 19 W.	Pan American Petroleum Corp., No. 1–B Navajo	San Juan.
33	Sec. 17, T. 31 N., R. 19 W.	The Superior Co., Navajo X No. 1	San Juan.
34	Sec. 4, T. 31 N., R. 18 W.	Humble Oil & Refining Co., No. 1–H Navajo	San Juan.
35	Sec. 8, T. 31 N., R. 18 W.	Humble Oil & Refining, No. 1–C Navajo	San Juan.
36	Sec. 15, T. 31 N., R. 18 W.	Humble Oil & Refining Co., Navajo Tract 24 No. 1	San Juan
37	Sec. 22, T. 31 N., R. 18 W.	Standard Oil Co. of Texas, Navajo Tribal 24 No. 22–1	San Juan.
38	Sec. 29, T. 31 N., R. 18 W.	Cactus Drilling Corp., Cactus Navajo 'A' No. 1	San Juan.
39	Sec. 35, T. 31 N., R. 18 W.	Standard Oil Co. of Texas, Navajo Tribal No. 1–21	San Juan.
40	Sec. 6, T. 31 N., R. 17 W.	Honolulu Oil Corp., Navajo No. 1	San Juan.
41	Sec. 22, T. 31 N., R. 17 W.	Reynolds Mining Corp., No. 1 Navajo-Lease 7652	San Juan.
42	Sec. 27, T. 31 N., R. 17 W.	Three States Natural Gas Co., Navajo No. 1	San Juan.
43	Sec. 34, T. 31 N., R. 17 W.	The Texas Company, No. 3–A Navajo	San Juan.
44	Sec. 3, T. 31 N., R. 16 W.	Standard Oil Co. of Texas, No. 1–6 Navajo Ute	San Juan.
45	Sec. 2, T. 31 N., R. 14 W.	Stanolind Oil & Gas Co., No. 7 Ute Indian	San Juan.
46	Sec. 10, T. 31 N., R. 14 W.	Pan American Petroleum Corp., No. 1–D Ute Mtn Tribal.	San Juan.
47	Sec. 15, T. 31 N., R. 14 W.	Riddle & Gottlieb, Ute Mountain Tribal No. 1	San Juan.
48	Sec. 35, T. 31 N., R. 4 W.	Southland Royalty Co., Chicosa Canyon No. 1	Rio Arriba.
49	Sec. 13, T. 30 N., R. 21 W.	Pan American Oil Corp., Navajo Tribal 'AD' No. 1	San Juan.
50	Sec. 5, T. 30 N., R. 20 W.	John H. Hill, Atlantic Navajo No. 1	San Juan.
51	Sec. 23, T. 30 N., R. 20 W.	Pure Oil Co. & Ohio Oil Co., No. 1–11 Navajo.	San Juan.
52	Sec. 24, T. 30 N., R. 20 W.	Amerada Petroleum Corp., No. 1 Navajo-Tract 10.	San Juan.
53	Sec. 12, T. 30 N., R. 19 W.	Sinclair Oil & Gas Co., Navajo Tribal 4000–San Juan No. 1.	San Juan.
54	Sec. 8, T. 30 N., R. 18 W.	Texaco, Inc., Navajo Tribal AP–IX	San Juan.
55	Sec. 11, T. 30 N., R. 18 W.	Standard Oil Co. of Texas, Navajo Tribal 22 No. 11–1	San Juan.
56	Sec. 14, T. 30 N., R. 18 W.	Cactus Drilling Corp., Navajo B No. 1	San Juan.
57	Sec. 5, T. 30 N., R. 17 W.	Phillips Petroleum, Navajo No. 1	San Juan.
58	Sec. 15, T. 30 N., R. 17 W.	Standard Oil Co. of Texas, Navajo Tribal 130 No. 15–1	San Juan.
59	Sec. 23, T. 30 N., R. 16 W.	Stanolind Oil & Gas Co., No. 1 O.J. Hoover	San Juan.
60	Sec. 31, T. 30 N., R. 16 W.	Humble Oil & Refining Co., No. 2–K Navajo	San Juan.
61	Sec. 11, T. 30 N., R. 14 W.	Humble Oil & Refining Co., North Kirtland Unit No. 1	San Juan.
62	Sec. 28, T. 30 N., R. 14 W.	Mountain Fuel Supply Co., Fruitland No. 1	San Juan.
63	Sec. 3, T. 30 N., R. 11 W.	Southwest Production Co., No. 1 Bandy	San Juan.
64	Sec. 14, T. 30 N., R. 8 W.	Delhi-Taylor Oil Corp., Florance-Federal No. 50	San Juan.
65	Sec. 6, T. 30 N., R. 1 E.	Dugan Production Corp., No. 35 La Corina	Rio Arriba.
66	Sec. 2, T. 29 N., R. 19 W.	Continental Oil Co., Rattlesnake No. 136	San Juan.
67	Sec. 12, T. 29 N., R. 19 W.	Continental Oil Co., Rattlesnake No. 142	San Juan.

TABLE 1.—*Number, location, operator, and well name of geophysical logs used in this report*—Continued

No.	Location	Operator and well name	County
New Mexico—Continued:			
68	Sec. 13, T. 29 N., R. 19 W.	Continental Oil Co., Rattlesnake No. 147	San Juan.
69	Sec. 19, T. 29 N., R. 18 W.	Continental Oil Co., Kern County Rattlesnake No. 1.	San Juan.
70	Sec. 21, T. 29 N., R. 18 W.	Kern County Land Co., No. 1–21 Shell-Navajo	San Juan.
71	Sec. 1, T. 29 N., R. 17 W.	Pan American Petroleum Corp., No. 1–C Navajo	San Juan.
72	Sec. 11, T. 29 N., R. 17 W.	San Juan Drilling Co., No. 1 Navajo-Fred Hamrah	San Juan.
73	Sec. 12, T. 29 N., R. 17 W.	Stanolind Oil & Gas Co., No. 1 Navajo	San Juan.
74	Sec. 20, T. 29 N., R. 17 W.	Zoller & Danneburg, Pajarito Navajo No. 1	San Juan.
75	Sec. 25, T. 29 N., R. 17 W.	M.M. Garrett, No. 1 Navajo	San Juan.
76	Sec. 30, T. 29 N., R. 17 W.	Amerada Petroleum Corp., Navajo Tract 20 No. 2.	San Juan.
77	Sec. 31, T. 29 N., R. 17 W.	Amerada Petroleum Corp., Navajo No. 1	San Juan.
78	Sec. 19, T. 29 N., R. 16 W.	Stanolind Oil & Gas Co., U.S.G. No. 13	San Juan.
79	Sec. 18, T. 29 N., R. 15 W.	Pure, Sun, Humble, 1–2 Navajo	San Juan.
80	Sec. 1, T. 29 N., R. 12 W.	Tennessee Gas & Oil Co., No. 1 USA-Dudley Cornell	San Juan.
81	Sec. 7, T. 29 N., R. 5 W.	El Paso Natural Gas Co., No. 50 SJU 29–5	Rio Arriba.
82	Sec. 27, T. 28 N., R. 19 W.	Amerada Petroleum Corp., Navajo No. 1–32	San Juan.
83	Sec. 13, T. 28 N., R. 18 W.	Champlin Petroleum Co., Navajo 1–12	San Juan.
84	Sec. 27, T. 28 N., R. 17 W.	Sunray DX, Navajo Table Mesa No. 1	San Juan.
85	Sec. 33, T. 28 N., R. 17 W.	Continental Oil Co., Table Mesa No. 28	San Juan.
86	Sec. 16, T. 28 N., R. 13 W.	Pan American Petroleum Corp., No. 1 Water Well	San Juan.
87	Sec. 13, T. 28 N., R. 11 W.	Southern Union Production Co., Angel Peak 22–B	San Juan.
88	Sec. 14, T. 28 N., R. 7 W.	Delhi-Taylor Oil Corp., San Juan Unit 28–7 No. 136	Rio Arriba.
89	Sec. 6, T. 28 N., R. 2 W.	Continental Oil Co., No. 1 South Dulce	Rio Arriba.
90	Sec. 26, T. 28 N., R. 1 E.	C & J Drilling, El Poso Ranch No. 1	Rio Arriba.
91	Sec. 33, T. 28 N., R. 1 E.	Derby Drilling Co., Jicarilla-Apache No. L.	Rio Arriba.
92	Sec. 14, T. 28 N., R. 3 E.	Southwestern Exploration Co., Martinez No. 1	Rio Arriba.
93	Sec. 28, T. 28 N., R. 4 E.	Coquina Oil Corp., Esquibel No. 1	Rio Arriba.
94	Sec. 7, T. 27 N., R. 20 W.	Texaco, Inc., Navajo AW No. 1	San Juan.
95	Sec. 21, T. 27 N., R. 19 W.	Northwest Pipeline Corp., Barbara Kay No. 2	San Juan.
96	Sec. 28, T. 27 N., R. 19 W.	Texaco, Inc., Navajo AS No. 1	San Juan.
97	Sec. 34, T. 27 N., R. 18 W.	Sinclair Oil & Gas Co., Navajo Tribal 141 No. 1	San Juan.
98	Sec. 3, T. 27 N., R. 17 W.	Continental Oil Co., No. 3–18 Table Mesa	San Juan.
99	Sec. 4, T. 27 N., R. 17 W.	Continental Oil Co., No. 24 Table Mesa	San Juan.
100	Sec. 9, T. 27 N., R. 17 W.	Continental Oil Co., Table Mesa No. 29	San Juan.
101	Sec. 20, T. 27 N., R. 17 W.	Amerada Petroleum Corp., Navajo tract 4 No. 1	San Juan.
102	Sec. 19, T. 27 N., R. 16 W.	Continental Oil Co., Chaco Wash Navajo No. 1	San Juan.
103	Sec. 25, T. 26 N., R. 20 W.	Gulf Oil Co., USA, Navajo 'BB' No. 1	San Juan.
104	Sec. 5, T. 26 N., R. 19 W.	Amerada Petroleum Corp., Navajo Tract 381 No. 1	San Juan.
105	Sec. 8, T. 26 N., R. 18 W.	Pan American Petroleum Corp., Navajo Tribal 'P' No. 3.	
106	Sec. 10, T. 26 N., R. 18 W.	Southern Gulf Production Co., No. 3 Navajo Tocito	San Juan.
107	Sec. 3, T. 26 N., R. 11 W.	El Paso Natural Gas Products, No. 1–D Delhi-Taylor Unit	San Juan.
108	Sec. 12, T. 26 N., R. 10 W.	El Paso Natural Gas Co., Huerfano 265	San Juan.

(fig. 1), the Ignacio consists mainly of white, reddish-brown, and light-brown conglomerate; feldspathic and quartzose sandstone; purple to green, burrowed, micaceous mudstone and siltstone; and minor dolomite. The sandstone is very coarse to fine grained and commonly contains angular clasts of potassium feldspar; ferromagnesian and titanomagnetite accessory minerals are sparse to abundant. Bedding is thin to thick in tabular layers with small- to medium-scale crossbeds. The sandstone is commonly silicified and resistant to erosion and weathers to angular ledges and cliffs.

The Ignacio is as thick as 150 ft (46 m) in the northwest part of the Reservation and thins to about 30 ft (10 m) in the Piedra River canyon about 20 mi (32 km) west of Pagosa Springs (fig. 5). In some places, such as at Bakers Bridge north of Durango, the Ignacio is absent due to onlap onto Proterozoic rocks (Baars and Ellingson, 1984, p. 11). Irwin (1977) interpreted about 50 ft (15 m) of strata as Ignacio Quartzite in the Stanolind No. 6–B Ute Indian drill hole, which is located south of Ignacio (sec. 17, T. 33 N., R. 7 W., La Plata County, Colo.). The Ignacio is not recognized on

TABLE 2. *Number, name, location, and source of outcrop measured sections used in this report*

No.	Name	Location	County	Source
Colorado:				
1	Dove Creek	Sec. 9, T. 40 N., R. 17 W.	Dolores	Craig and others (1959).
2	Coalbank Pass	Sec. 29, T. 40 N., R. 8 W.	San Juan	Baars and Knight (1957).
3	McPhee	Sec. 28, T. 39 N., R. 16 W.	Montezuma	Craig and others (1959).
4	Stoner	Sec. 3, T. 38 N., R. 14 W.	Montezuma	Craig and others (1959).
5	Stoner	Sec. 1, T. 38 N., R. 13 W.	Montezuma	Stewart and others (1972).
6	Stag Mesa	Sec. 19, T. 38 N., R. 7 W.	La Plata	Baars and Knight (1957).
7	Rockwood Quarry	Sec. 12, T. 37 N., R. 9 W.	La Plata	Baars and Knight (1957).
8	Hermosa	Sec. 26, T. 37 N., R. 9 W.	La Plata	Wengerd and Matheny (1957).
9	Endlich Mesa	Sec. 11, T. 37 N., R. 7 W.	La Plata	Baars and Knight (1957).
10	Lower McElmo Canyon.	Sec. 21, T. 36 N., R. 18 W.	Montezuma	Craig and others (1959).
11	Upper McElmo Canyon/ Goodman Canyon.	Sec. 28, T. 36 N., R. 17 W.	Montezuma	Craig and others (1959), B. Bartleson (unpub. data, 1980).
12	Junction Creek	Sec. 25, T. 36 N., R. 10 W.	La Plata	Stewart and others (1972).
13	Durango	Sec. 22, T. 36 N., R. 9 W.	La Plata	Baars (1962).
14	Fall Creek Ranch	Sec. 32, T. 36 N., R. 9 W.	La Plata	B. Bartleson (unpub. data, 1980).
15	Los Pinos	Sec. 35, T. 36 N., R. 7 W.	La Plata	Craig and others (1959).
16	Mosca Creek	Sec. 17, T. 36 N., R. 5 W.	Archuleta	Condon and others (1984).
17	Upper Piedra	Sec. 4, T. 36 N., R. 3 W.	Archuleta	Craig and others (1959).
18	Durango	Sec. 3, T. 35 N., R. 9 W.	La Plata	Stewart and others (1972).
19	Durango	Sec. 17, T. 35 N., R. 9 W.	La Plata	Craig and others (1959).
20	Piedra River	Sec. 17, T. 35 N., R. 4 W.	Archuleta	Read and others (1949).
21	Piedra River	Sec. 31, T. 34 N., R. 4 W.	Archuleta	Stewart and others (1972).
22	Lower Piedra	Sec. 5, T. 34 N., R. 4 W.	Archuleta	Craig and others (1959).
Arizona:				
1	Horse Mesa	Sec. 17, T. 38 N., R. 31 E.	Apache	Condon (1985).
New Mexico:				
1	Beclabito Dome	Sec. 24, T. 30 N., R. 21 W.	San Juan	Condon (1985).
2	Beclabito Dome	Sec. 7, T. 30 N., R. 20 W.	San Juan	A.C. Huffman, Jr. (unpub. data, 1981).
3	Oak Springs	Sec. 13, T. 29 N., R. 21 W.	San Juan	Craig and others (1959), A.C. Huffman, Jr. (unpub. data, 1983).
4	White Rock	Sec. 24, T. 27 N., R. 21 W.	San Juan	Corken (1979).
5	Beautiful Mountain	Sec. 11, T. 26 N., R. 21 W.	San Juan	Corken (1979).

the east side of the Reservation but thickens markedly to the west and northwest (fig. 5).

Sediments in the lower part of the Ignacio Quartzite were deposited subaerially in streams and on alluvial fans. The conglomerate in the formation was apparently derived from nearby uplifted Proterozoic fault blocks and, in some cases, consists of angular boulders that were not transported far (Baars and See, 1968, p. 338; Baars and Ellingson, 1984, p. 11). The upper part of the Ignacio, which consists of fine-grained clastic rocks and dolomite, is a shallow-shelf assemblage of material that was deposited by the eastward transgressing sea of the Cordilleran miogeocline (Baars, 1966, p. 2085; Baars and See, 1968, p. 340). Assignment of the Ignacio to the Late Cambrian is on the basis of meager fossil data (Cross and others, 1905; Rhodes and Fisher, 1957). There is no production of hydrocarbons or any other economic resource from the Ignacio in the vicinity of the Reservation.

ORDOVICIAN AND SILURIAN ROCKS

Ordovician or Silurian rocks have not been found in the area of the Southern Ute Reservation or surrounding areas, but they are present in central and northern Colorado. Their absence in southwestern Colorado may be due to nondeposition or to post-Middle Devonian erosion. At some time between deposition of the Ignacio Quartzite and overlying Devonian rocks tectonic activity must have been sufficient to have formed the previously mentioned horsts and grabens in which the Ignacio is selectively preserved (Stevenson and Baars, 1986). The tectonism, however,

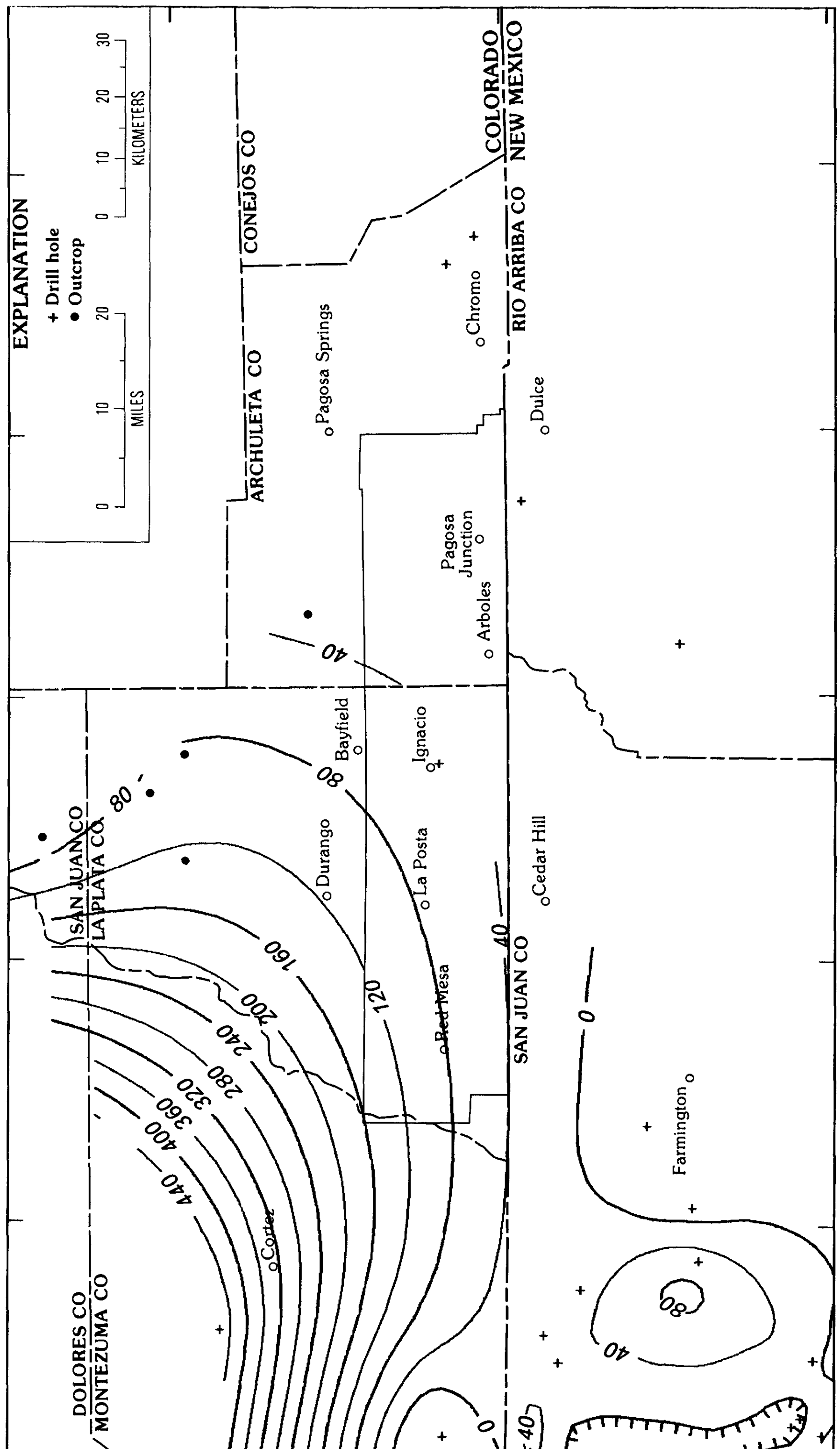

FIGURE 5.—Isopach map of the Ignacio Quartzite. Contour interval is 40 feet. Modified from unpublished data by A.C. Huffman, Jr., and S.M. Condon (1990).

·vas not severe enough to have caused angular discordance between the Ignacio and overlying units in outcrops adjacent to the Reservation.

DEVONIAN ROCKS

Upper Devonian rocks on the Southern Ute Indian Reservation consist of the McCracken Sandstone Member and upper member of the Elbert Formation and the overlying Ouray Limestone (fig. 3). The aggregate thickness of Devonian rocks on the Reservation ranges from 50 to 200 ft (15–61 m). The Upper Devonian Aneth Formation (fig. 3) is absent on the Reservation and is therefore not discussed in this report. The Upper Devonian Elbert Formation (Cross, 1904) unconformably overlies the Ignacio Quartzite; it overlies Precambrian rocks locally where the Ignacio is absent. In some places, such as at Ouray, Colo., and possibly in the Piedra River canyon, the Elbert overlies Precambrian rocks with sharp angular unconformity. The Elbert was divided into the basal McCracken Sandstone Member and the upper member by Knight and Cooper (1955, p. 56). Although the McCracken is a hydrocarbon producer in parts of Utah and Arizona, it has not been productive on the Reservation. Neither the upper member of the Elbert Formation nor the Ouray Limestone have any known economic potential on the Reservation, although the Ouray has been quarried for road metal at Rockwood Quarry, north of Durango.

ELBERT FORMATION

McCRACKEN SANDSTONE MEMBER

The McCracken Sandstone Member consists of gray to brown sandstone, brown and gray dolomite, and greenish-gray shale (Knight and Cooper, 1955, p. 56). The dominant lithology is very fine to coarse grained sandstone. Where observed, north of Durango and in the Piedra River canyon, sandstone of the McCracken is quartzose, in contrast to the underlying feldspathic Ignacio Quartzite; feldspar that does occur in the McCracken appears to be plagioclase. Accessory minerals are sparse in the McCracken. The lithologies of both the Ignacio and McCracken, however, could be expected to change areally depending on the lithologies of their sources. At outcrops north of Durango and in the Piedra River canyon, bedding is thin to thick in laterally extensive, tabular sheets that have small- to medium-scale crossbeds. The sandstone is highly silicified and weathers to ledgy cliffs. Although the McCracken and the Ignacio Quartzite are somewhat different mineralogically, they look similar in outcrops. This similarity led to misidentifications and miscorrelations in some earlier studies.

The thickness of the McCracken is 112 ft (34 m) in the drill hole where it was originally defined (Shell Oil Co., No. 1 Bluff Unit; sec. 32, T. 39 S., R. 23 E., San Juan County, Utah; Knight and Cooper, 1955, p. 56). This member generally ranges from 0 to 140 ft (0–43 m) thick elsewhere in the subsurface (fig. 6). Baars (1966, p. 2089) reported that the McCracken is best developed on the flanks of Paleozoic fault blocks but is absent over the tops of several blocks. Baars and Campbell (1968, p. 35) noted that the McCracken grades to arenaceous dolomite between the Paleozoic fault blocks. The McCracken, unlike the Ignacio, does not contain cobbles or boulders near the Paleozoic fault blocks. This lithologic difference led Baars and See (1968, p. 342) to the conclusion that the faults were not active during deposition of the McCracken. Like the Ignacio, the McCracken apparently did not form or was later eroded, in the Four Corners area (fig. 6). The distribution of the McCracken is poorly constrained on the Reservation because of the lack of deep drilling.

The McCracken is composed of shallow-marine, nearshore sediments that were deposited during a eustatic sea-level rise in the Late Devonian (Sandberg and others, 1989). Parker and Roberts (1966, p. 2413) interpreted the McCracken and other Elbert sandstones as a shallow-shelf assemblage of barrier-bar, wave-break point-bar, and blanket sand deposits. C.A. Sandberg (oral commun., 1988) identified small fragments of Devonian fish bones in a hand specimen of the McCracken that was collected by me in the Piedra River canyon.

UPPER MEMBER

The upper member of the Elbert consists of generally poorly exposed, thinly bedded, brownish-gray, sandy dolomite and sandstone; green to red shale; and minor anhydrite. Excellent exposures of the unit can be found in the area of the First Box anticline (Condon and others, 1984) in the Piedra River canyon. The upper member commonly ranges from 150 to 250 ft (46–76 m) in thickness in areas to the west of the Reservation (fig. 7) and thins eastward to about 25 ft (7.5 m) in the Piedra River area (Read and others, 1949). The unit is not recognized east of Chromo, Colo., or southeast of Dulce, N. Mex. (fig. 7).

The presence of salt casts, stromatolites, and fish remains suggests that sediments of the upper member were deposited in a shallow-water tidal-flat environment (Baars and Campbell, 1968, p. 35; Baars

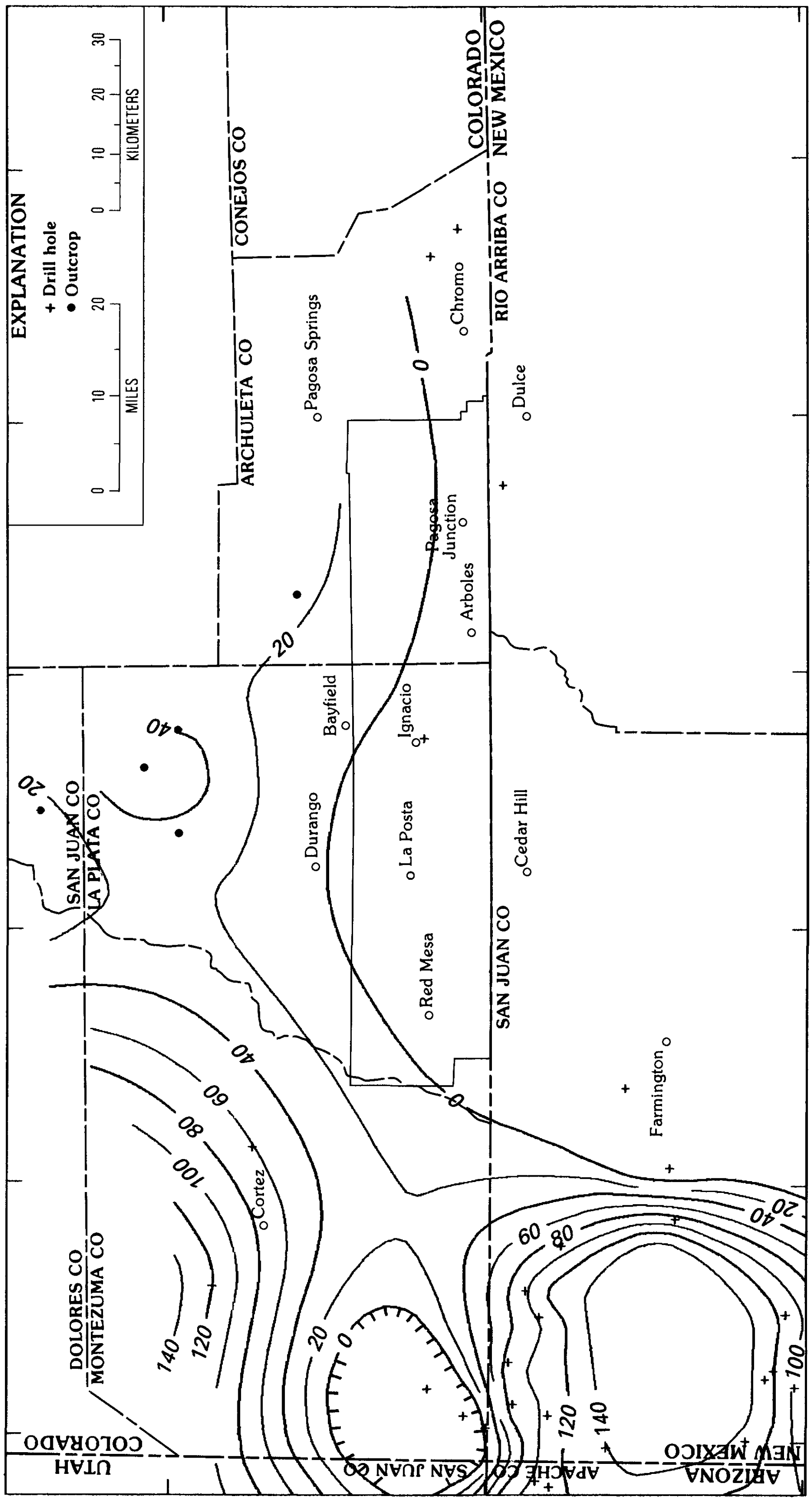

Figure 6.—Isopach map of the McCracken Sandstone Member of the Elbert Formation. Contour interval is 20 feet. Modified from unpublished data by A.C. Huffman, Jr., and S.M. Condon (1990).

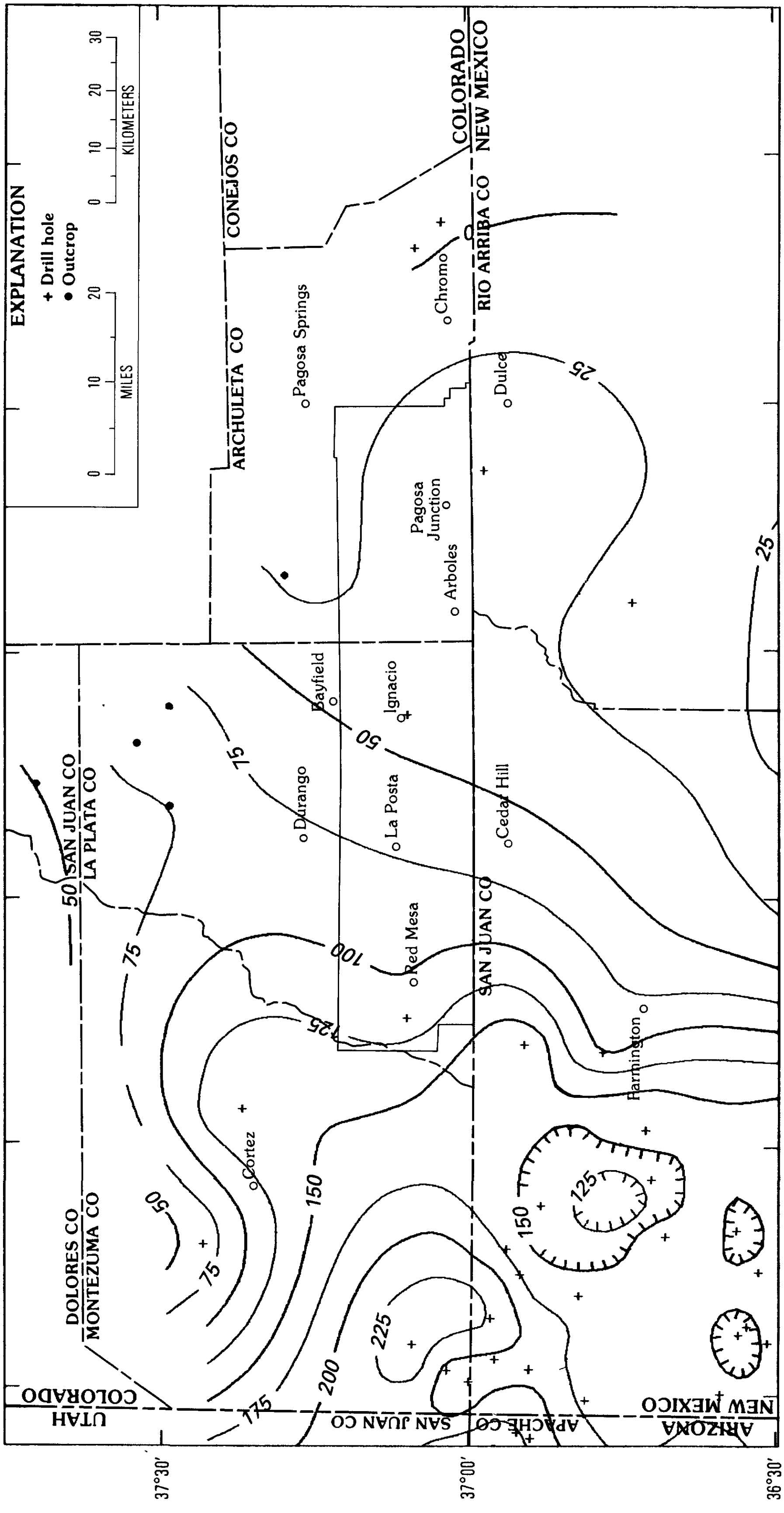

FIGURE 7.—Isopach map of the upper member of the Elbert Formation. Contour interval is 25 feet. Modified from unpublished data by A.C. Huffman, Jr., and S.M. Condon (1990).

and See, 1968, p. 341). Sediments of the upper member of the Elbert Formation were deposited in the gradually deepening waters of a Late Devonian marine transgression (Sandberg and others, 1989). The even distribution and lack of pinchouts of the upper member on Paleozoic fault blocks suggested to Baars and See (1968, p. 342) that the region was not tectonically active during the deposition of the unit. The upper member conformably overlies the McCracken Sandstone Member where the McCracken is present. Where the McCracken is not present the upper member rests unconformably on Proterozoic or Cambrian rocks.

OURAY LIMESTONE

The Upper Devonian Ouray Limestone (Spencer, 1900) conformably overlies the Elbert Formation. The Ouray is dark-brown to light-gray, dense, argillaceous limestone with local green clay partings. The basal bed of the Ouray is a tan dolomite in many places (Baars and Knight, 1957, p. 120); a green clay bed as thick as 15 ft (4.5 m) commonly occurs at the top. Abundant brachiopods, gastropods, crinoids, and foraminiferans have been found in the Ouray (Baars and Campbell, 1968, p. 37). The Ouray generally thickens from a pinchout near the east side of the Reservation to 100 ft (30 m) near the Utah-Colorado State line (fig. 8).

The marine fauna and widespread extent of the Ouray Limestone (more than 50,000 mi^2 (129,500 km^2) according to Parker and Roberts, 1966, p. 2416) indicate deposition in a shallow sea. The sea occupied a cratonic shelf east of the Cordilleran miogeocline and west of the North American craton. The sediments of the Ouray were deposited during the last major transgression of the Late Devonian sea (Sandberg and others, 1989, p. 206).

MISSISSIPPIAN ROCKS

LEADVILLE LIMESTONE

The Leadville Limestone, which is the only formation of the Mississippian System in the area of the Southern Ute Reservation, was named by Emmons and Eldridge (1894) for typical exposures of the unit near Leadville, Colo. The Leadville was interpreted to unconformably overlie the Ouray Limestone by Armstrong and others (1980 p. 86). Although compelling faunal evidence exists for a long hiatus between the highest conodont fauna in the Ouray and the lowest diagnostic foraminiferan fauna in the Leadville (C.A. Sandberg, written commun., 1990), Baars and Ellingson (1984, p. 14) disputed the presence of an unconformity at the position picked by Armstrong and others (1980).

The Leadville consists of yellowish-brown and light- to dark-gray, finely to coarsely crystalline, fossiliferous dolomite and limestone. Dolomite is more common than limestone in the lower, thin- to medium-bedded part of the unit, and limestone is the dominant lithology of the upper, more massively bedded part. The top of the Leadville, which was deeply eroded into karst topography before deposition of the overlying sediments, has joint and cavern fillings of reddish siltstone and mudstone. This residual material filtered downward after lithification of the Leadville and was not a primary depositional feature. The Leadville thickens from nearly zero on the east side of the Reservation to about 250 ft (76 m) on the west side (fig. 9).

The Leadville has produced oil and (or) gas at the Lisbon Southeast field, northwest of the Southern Ute Reservation (Irwin, 1983, p. 844), and at several fields in New Mexico (Fassett, 1983b, p. 851), but there has been no production from the Leadville on the Reservation. The Leadville has been very important in production of carbon dioxide and helium in the region (Gerling, 1983; Casey, 1983). Although no carbon dioxide or helium has been produced from the Leadville on the Reservation, the limited amount of deep drilling does not disallow the presence of these gases. The Leadville has also been quarried for road metal at Rockwood Quarry, north of Durango.

The Leadville of southwest Colorado and adjacent areas was formed during two transgressive episodes in the Mississippian (Armstrong and Holcomb, 1989, p. D12). Baars and See (1968, p. 344) and Armstrong and Holcomb (1989, p. D1) interpreted the sediments of the Leadville to have been deposited under a variety of depositional environments. They suggested that the sediments of the lower dolomitic part were deposited under shallow-water tidal-flat conditions and that those of the upper part were deposited in diverse marine environments, which ranged from low-energy stable-shelf conditions to high-energy shoals. Baars and See (1968, p. 344) reported that the variable nature of the upper Leadville in parts of southwestern Colorado arose from paleogeographical features that were controlled by Paleozoic structural elements.

PENNSYLVANIAN ROCKS

Pennsylvanian rocks, which total 1,000–3,000 ft (305–914 m) in thickness, are present on the Southern Ute Reservation. Formations, from oldest to youngest, are the Molas Formation and Hermosa Group, which

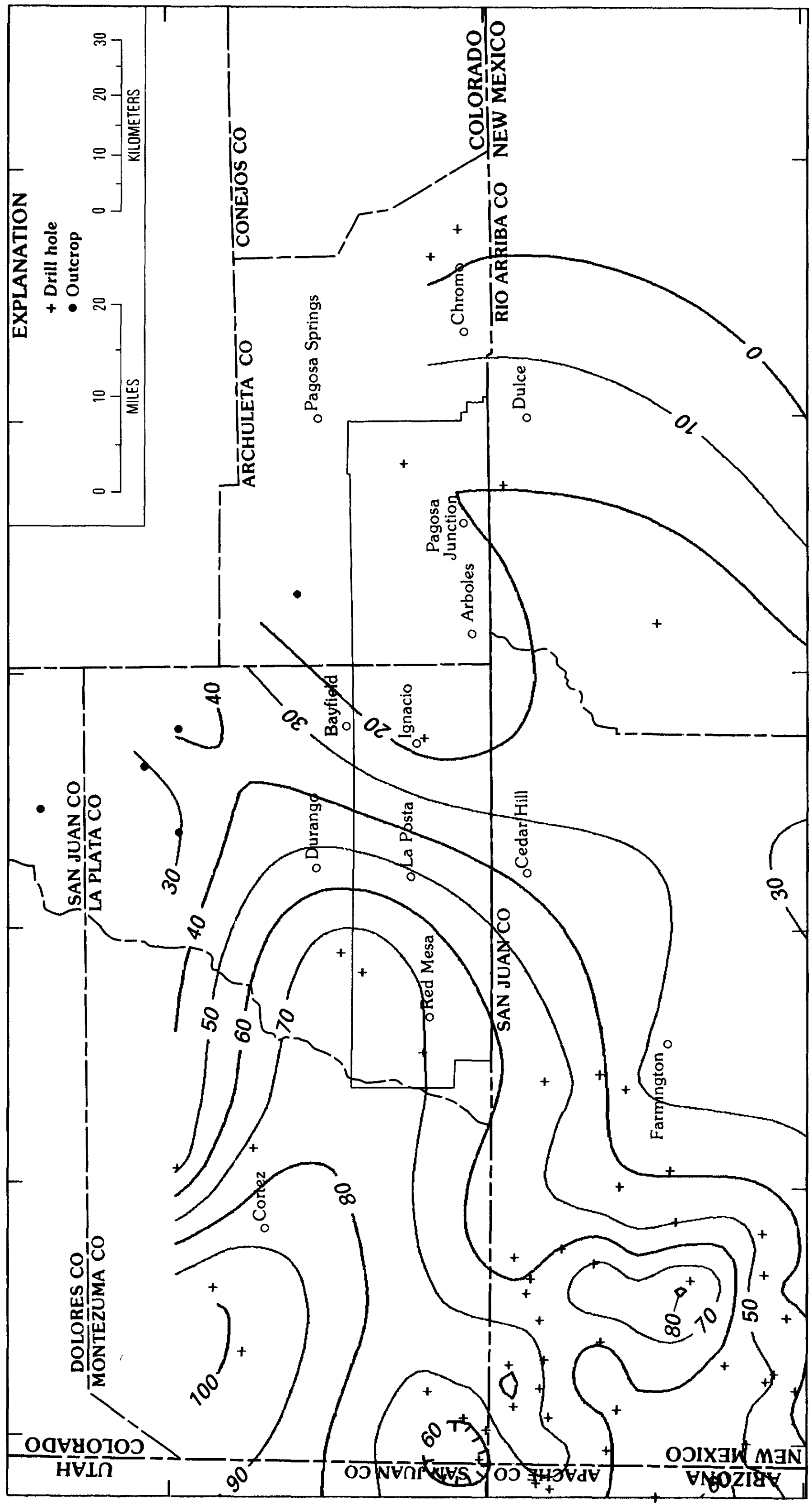

FIGURE 8.—Isopach map of the Ouray Limestone. Contour interval is 10 feet. Modified from unpublished data by A.C. Huffman, Jr., and S.M. Condon (1990).

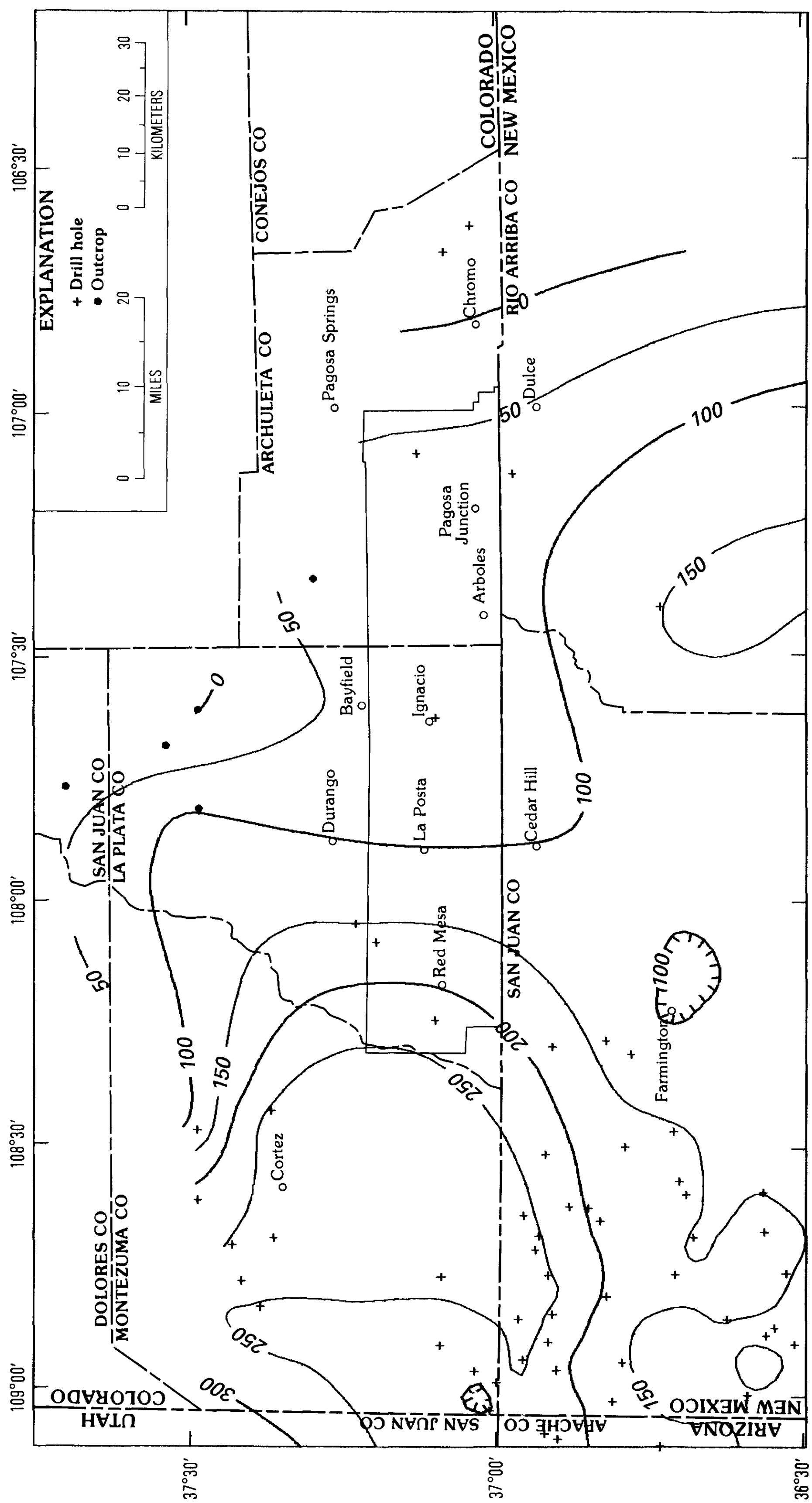

FIGURE 9.—Isopach map of the Leadville Limestone. Contour interval is 50 feet. Modified from unpublished data by A.C. Huffman, Jr., and S.M. Condon (1990).

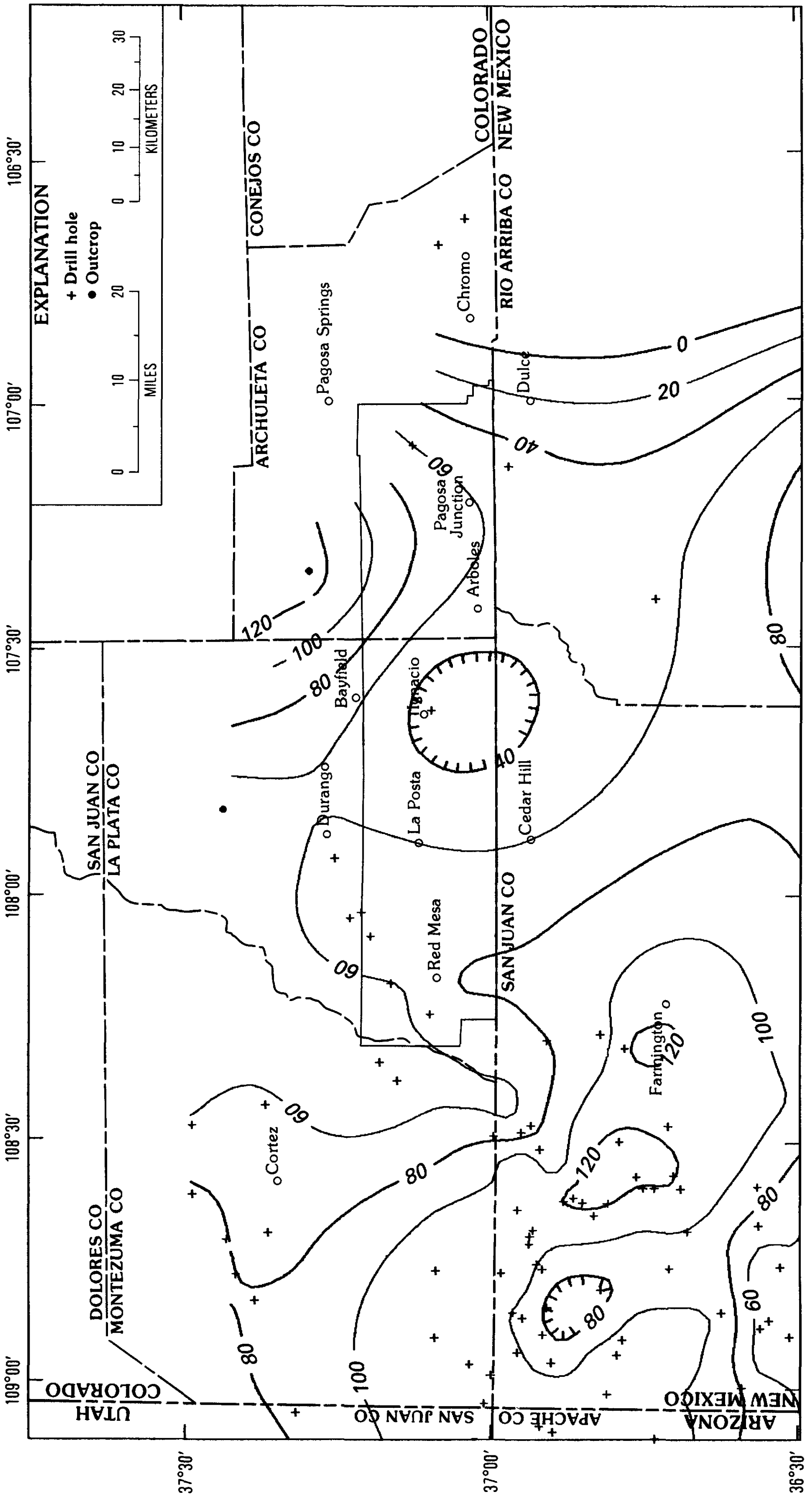

FIGURE 10.—Isopach map of the Molas Formation. Contour interval is 20 feet. Modified from Huffman and Condon (in press).

consists of the Pinkerton Trail, Paradox, and Honaker Trail Formations. Although the age of the Molas may range from Late Mississippian to Early Pennsylvanian (Armstrong and Holcomb, 1989, p. D11), the entire unit is discussed here in the context of the Pennsylvanian. The Rico Formation is transitional between the Pennsylvanian and Permian and is discussed under a separate heading below. In the Piedra River canyon, north of the Reservation, the formations of the Hermosa Group cannot be separated; in that area the unit is recognized as the undivided Hermosa Formation. Pennsylvanian rocks unconformably overlie Mississippian or older rocks throughout the area.

Pennsylvanian rocks are important sources of oil and gas throughout the Four Corners area, including the western side of the Reservation (Fassett, 1983a; Huffman, 1987, p. 17). The scattered deep tests elsewhere on the Reservation have been unproductive.

MOLAS FORMATION

The Molas Formation was named by Cross and others (1905, p. 4). Later, the Molas was divided into three members: the basal Coalbank Hill Member, the middle member, and the upper member (Merrill and Winar, 1958, 1961). All three members are not present in all areas. The Molas averages about 60 ft (18 m) in thickness across much of the Reservation but thins to less than 40 ft (12 m) in the central part (fig. 10). The Molas thickens northward in the Piedra River area and westward in the Farmington, N. Mex., area (fig. 10). The isopach map of the Molas (fig. 10) is of the entire formation.

COALBANK HILL MEMBER

The Coalbank Hill Member consists of red, purplish-red, and reddish-brown siltstone and of chert- and limestone-pebble conglomerate. The thickness of the member is variable and ranges from a pinchout in some places to 56 ft (17 m) in the type area north of Durango (Merrill and Winar, 1958, p. 2118). The Coalbank Hill is a residual soil (terra rossa) deposit that developed on top of the Leadville Limestone. Baars and Ellingson (1984, p. 15) noted that so much clay from the paleosol of the Molas had filtered down into cracks, crevices, and caverns of the Leadville Limestone that it rendered the limestone unusable as a scrubbing agent in coal-fired generating plants. In some areas, such as at Coalbank Hill itself, the Leadville is absent and the Molas rests unconformably on the Ouray Limestone (Merrill and Winar, 1958, p. 2117). No age-diagnostic fossils that could be used to date precisely the Coalbank Hill Member have been found. Merrill and Winar considered the Mississippian-Pennsylvanian boundary to lie within the Coalbank Hill or the overlying middle member. If so, the Coalbank Hill may be correlative with the lithologically similar Log Springs Formation of the southeastern San Juan Basin.

MIDDLE MEMBER

The middle member is a heterogeneous unit that consists of interbedded reddish-brown shale, siltstone, mudstone, sandstone, and conglomerate. The conglomerate consists of mainly chert pebbles, but limestone pebbles are present locally (Merrill and Winar, 1961, p. 85). The middle member averages 40 ft (12 m) in thickness. Sediments of this member were deposited by streams that reworked the underlying paleosol or older rock units. Reworking of older rocks is indicated by a greater abundance of accessory minerals and sandstone and conglomerate beds in the middle member versus the underlying Coalbank Hill Member (Merrill and Winar, 1958, p. 2130). Merrill and Winar (1958, p. 2117) interpreted the middle member to unconformably overlie the Coalbank Hill Member.

The only way Merrill and Winar (1958, p. 2119) were able to distinguish the middle member from the upper member was by laboratory analysis of the clay composition of the units. The top of the middle member was defined as the point at which kaolinite is more abundant than illite. Merrill and Winar (1958, p. 2119) presented a list of characteristics of each member that aided in their field identification, but stated that the boundary could only be approximated. It is thus impossible to separate the middle and upper members with the meager subsurface control available in the Reservation.

UPPER MEMBER

The upper member consists of the same diverse lithologies, which range from shale to conglomerate, that compose the middle member; the unit additionally contains some beds of fossiliferous limestone. In contrast to the reddish-brown color of the lower members, the upper member also contains sandstone beds that are maroon, pink, and light gray. Sandstone units were described by Merrill and Winar as being more laterally continuous than those of the middle member. Limestones of the upper member contain marine fossils, including brachiopods, bryozoans, echinoderms, and foraminiferans (Merrill and Winar, 1958, p. 2123). The thickness of the upper member averages about 25 ft (8 m). The contact between the upper member of the Molas and the overlying Pinkerton Trail Formation is gradational.

Sediments of the upper member were deposited, in part, by streams that reworked preexisting Molas sediments and older rocks and, in part, by a transgressing sea. The material in the upper, fossiliferous limestone beds of the Molas was deposited in the gradually deepening Paradox basin which was to influence strongly the remainder of Pennsylvanian deposition in this region.

HERMOSA GROUP

The Hermosa Group, which consists of the basal Pinkerton Trail, the Paradox, and the Honaker Trail Formations, conformably overlies the Molas Formation. The Hermosa is a complex assemblage of marine and continental sediments that were deposited cyclically in the central basin and on the margins of the Paleozoic Paradox basin. The Hermosa ranges in thickness from about 400 ft (122 m) on the southeast side to about 2,800 ft (853 m) on the west side of the Reservation (fig. 11). Where the Hermosa Group cannot be divided into distinct lithologic formations, the unit is mapped as the undivided Hermosa Formation.

The configuration of the southeast end of the Paradox basin is evident on figure 11. The deepest part of the basin, which contains deposits of the Hermosa Group thicker than 2,000 ft (610 m), extends southeast-northwest and includes the west side of the Reservation. The area of thick deposits that extends southward from the Reservation into New Mexico was termed the "Cabezon accessway" by Wengerd and Matheny (1958). This area connected the central Paradox basin with other Pennsylvanian basins farther to the south. The Paradox basin was rimmed on the north and northeast by the ancestral Uncompahgre uplift and the San Luis uplift (a southeast extension of the Uncompahgre) and on the southwest by the Defiance-Zuni and Kaibab uplifts. These tectonically active areas were the source of clastic sediments that were shed into the basin during both Pennsylvanian and Permian time.

The Hermosa Group consists of four distinct, interbedded facies: The arkosic, shelf-clastic, shelf-carbonate, and evaporite facies (Peterson and Hite, 1969, p. 892). The arkosic facies consists of poorly sorted, conglomeratic arkose and micaceous siltstone. The arkose beds are lenticular and crossbedded. Arkose beds in the Animas River valley north of Durango show transport directions to the southwest (Girdley, 1968, p. 155), which indicates that the rocks were shed from the ancestral Uncompahgre and San Luis uplands to the northeast (Fetzner, 1960, p. 1396; Peterson and Hite, 1969, p. 892). Hite and Buckner (1981, p. 156) interpreted as turbidites the coarse clastic rocks that occur in a more basinward position to the southwest.

Read and others (1949) diagrammatically showed the extent of the arkosic facies in the Piedra River canyon. They indicated that the clastic rocks thin and pinch out southward in the canyon into interbedded limestones. Moreover, oxidized red shale and siltstone are increasingly abundant northward in this facies, which they interpreted to indicate deposition in a more landward direction to the north.

The shelf-clastic facies is mainly fine-grained, well-sorted sandstone that occurs on the gently sloping southwest side of the Paradox basin. The clastic sediments were most likely shed from the ancestral Kaibab and Defiance-Zuni uplands south and southwest of the Paradox basin (Fetzner, 1960, p. 1376; Peterson and Hite, 1969, p. 892). Hite and Buckner (1981, p. 156) attributed the distribution of these sediments to reworking of shoreline sandstones during episodes of rising sea level. The lighter fraction of these clastic sediments was carried seaward over the dense saline brines that filled the basin and contributed to the formation of the basin-wide black shales.

The shelf-carbonate facies consists of cyclic deposits of dolomite, limestone, and black, carbonaceous shale. These lithologies occur on the southeast, south, and southwest shelves of the central Paradox basin. In addition to the laterally extensive, tabular shelf-carbonate rocks of this facies, lenticular, mound-shaped accumulations of carbonate rock are also present. These carbonate mounds are buildups of the leaf-like alga *Ivanovia*, which thrived in the shallow-shelf environment (Choquette, 1983).

Porosity of the carbonate mounds commonly is 10 percent or more (Fassett, 1978b), which has made this facies important as an oil and gas reservoir in southeast Utah and in some parts of southwest Colorado. The oil field at Aneth, Utah, is in a large algal mound complex in this facies, and the Ismay field, near the Colorado-Utah State line, is in smaller algal-mound buildups.

The evaporite facies of the Hermosa is present on the west side of the Southern Ute Reservation and consists of as much as 1,650 ft (503 m) of cyclic deposits of halite, sylvite, carnallite, and secondary black shale, dolomite, limestone, and anhydrite. Halite composes 70–80 percent of the section in some parts of the Paradox basin (Peterson and Hite, 1969, p. 893). This facies contains at least 29 separate beds of halite, which are separated by interbeds of limestone, dolomite, anhydrite, and black shale (Hite, 1960, p. 87; Hite and Buckner, 1981, p. 150). Complex interbedding of the nonporous elements of the evaporite facies with

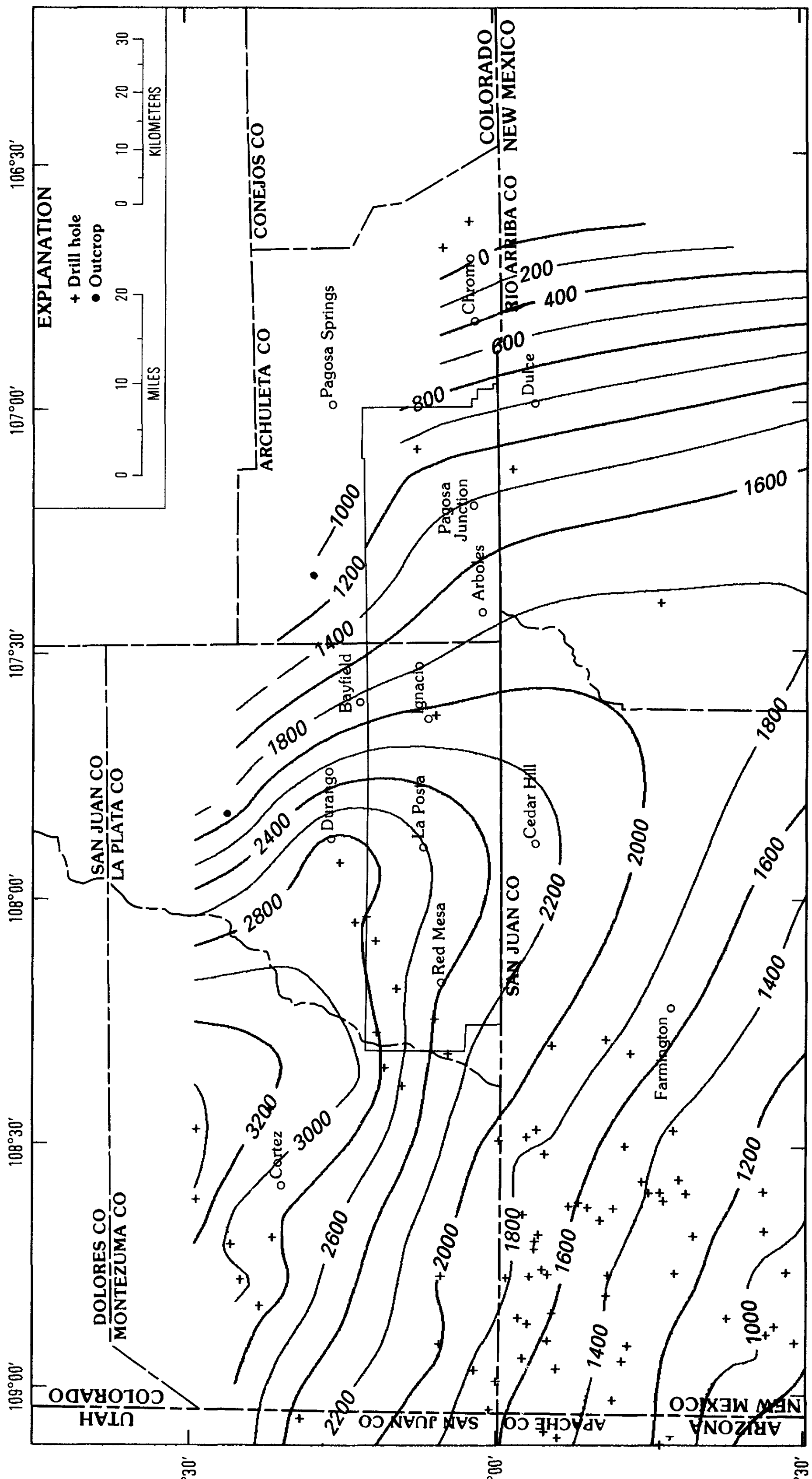

FIGURE 11.—Isopach map of the Hermosa Group. Contour interval is 200 feet. Modified from Huffman and Condon (in press).

the porous carbonate mounds of the shelf-carbonate facies led to ideal conditions for stratigraphic traps of hydrocarbons. The black, organic-rich shale beds that serve as the source of the hydrocarbons were formed under euxinic conditions. These shale beds, which extend throughout the Paradox basin from the central portion onto the shelves, are used widely for subsurface correlation.

The division of the Hermosa Group into its constituent formations is based solely on the ability to distinguish the Paradox Formation and equivalent strata from enclosing rocks of the group. If recognition of the Paradox is limited to only the areas in which evaporite rocks are found, the Paradox would extend only part way across the Southern Ute Reservation. If, however, equivalent rocks outside the evaporite facies are included with the Paradox, division of the group into the three formations can be made throughout the area. This latter method is used in this report and will be explained in more detail in the discussion of the Paradox Formation that follows.

PINKERTON TRAIL FORMATION

The Pinkerton Trail Formation (Wengerd and Strickland, 1954, p. 2168) overlies the Molas Formation and consists of light-gray to dark-gray, finely to coarsely crystalline, argillaceous to silicified limestone and minor dark-gray to black, highly carbonaceous shale. The Pinkerton Trail contains increasing amounts of coarse, clastic detritus northward from Durango (Fetzner, 1960, p. 1396, his fig. 8). Crinoids and fusulinids of Atokan and Desmoinesian age are common in the limestone (Wengerd and Strickland, 1954, p. 2169). The formation is about 85 ft (26 m) thick at Pinkerton Trail north of Durango and thickens southward and westward into the Paradox basin (Wengerd and Strickland, 1954, p. 2169; Wengerd and Matheny, 1958, p. 2065). On the Reservation it ranges from about 40 to 120 ft (12–36 m) in thickness (fig. 12). Excellent exposures of the Pinkerton Trail are along Colorado Highway 550 north of Durango (see Baars and Ellingson, 1984, for a roadlog of this area). Sediments of the Pinkerton Trail were deposited conformably on the Molas Formation after Early Pennsylvanian seas transgressed from the west and southeast (Wengerd, 1957, p. 135; Wengerd and Matheny, 1958, p. 2085).

PARADOX FORMATION AND EQUIVALENT ROCKS

The Paradox Formation, which was named by Baker and others (1933), conformably overlies the Pinkerton Trail Formation and is perhaps the most complex sedimentary rock unit in southwest Colorado. The Paradox has been divided into cyclic units (Baars and others, 1967), which are, in ascending order, the Alkali Gulch, Barker Creek, Akah, Desert Creek, and Ismay. These units are bounded by the black shale beds; correlation from the evaporite facies to the shelf-carbonate facies is made possible by recognition of the shale marker beds. The cyclic units are thus lithologically diverse and grade from salt and anhydrite of the Paradox Formation in the central part of the basin to equivalent shelf-carbonate rocks and sandstone on the outer margins of the basin. Most of the oil and gas production from the Paradox has been from the Desert Creek and Ismay.

Hite and Buckner (1981, p. 150) numbered the evaporite cycles from 1 to 29 (top to bottom) and showed that the maximum extent of the evaporite facies is in cycles 6–9 (Akah) and 13–19 (Barker Creek). The lateral extent of evaporite facies in the Alkali Gulch, Desert Creek, and Ismay zones is much less than that in the Akah and Barker Creek zones. For this report, the top of the Paradox was picked at the top of the Ismay zone (cycle 2). Cycle 1, which is more fully developed in Utah, was not correlated into the Reservation. The evaporite facies extends southeastward into Colorado and the Southern Ute Reservation where 1,000–1,800 ft (305–549 m) of sediments of the facies were deposited. Figure 13 shows the limits of salt, anhydrite, and black shale in the area of the Reservation.

Limiting recognition of the Paradox Formation to only the areas where salt or anhydrite occurs would place the eastern extent of the Paradox roughly halfway across the Reservation (fig. 13). However, rocks equivalent to the evaporite facies may be recognized in the eastern part of the Reservation and in areas to the south of the Reservation by correlation of shale marker beds and carbonate beds.

I believe that recognition of strata equivalent to the evaporite facies of the Paradox is important in reconstruction of the depositional and structural history of this region. Recognition of the rocks equivalent to the Paradox in areas outside the area of the evaporite facies also makes it possible to recognize the underlying Pinkerton Trail Formation and the overlying Honaker Trail Formation in those areas.

The sediments of the Paradox Formation and equivalent rocks were deposited in a subsiding, elongate trough that was oriented northwest-southeast and bounded by uplifts (Fetzner, 1960, p. 1376). Circulation of marine water of normal salinity into the Paradox basin was hindered by the bounding uplifts and by low, submarine barriers that connected the uplifts. Although a general rise of global sea level

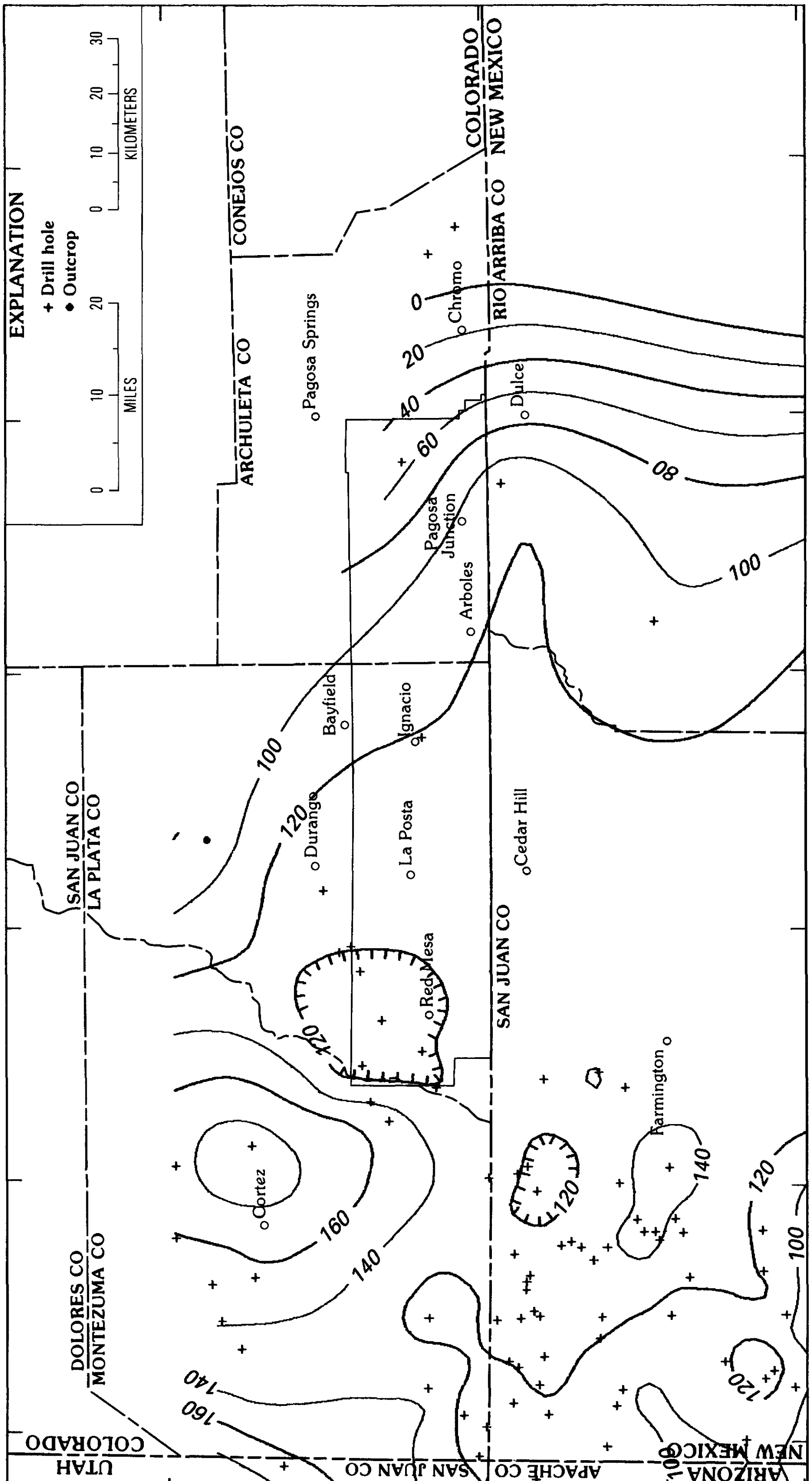

FIGURE 12.—Isopach map of the Pinkerton Trail Formation of the Hermosa Group. Contour interval is 20 feet. Modified from Huffman and Condon (in press).

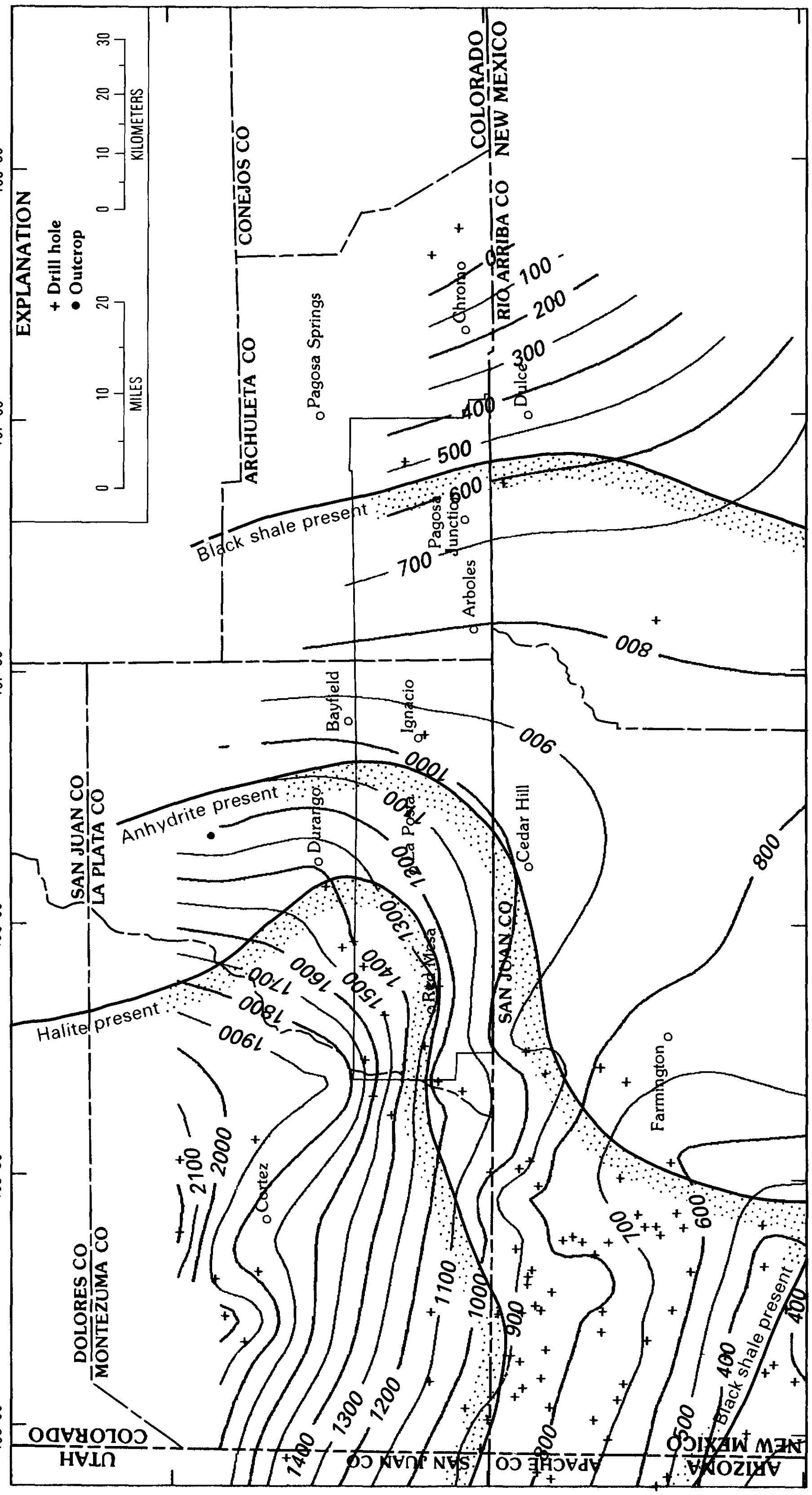

FIGURE 13.—Isopach map of the Paradox Formation and equivalent rocks of the Hermosa Group. Contour interval is 100 feet. Modified from Huffman and Condon (in press).

occurred during the Pennsylvanian (Vail and others, 1977), the Paradox basin underwent periodic episodes of rising and falling sea level. During times of lower sea level the basin was virtually cut off from the open ocean, which resulted in evaporation with limited recharge and led to the cyclicity of strata and the remarkable thicknesses of salt within the subsiding basin. Peterson and Hite (1969, p. 894) considered the Hogback monocline area (fig. 1) as the main accessway for circulation of normal marine water into the restricted waters of the Paradox basin.

Hite and Buckner (1981, p. 157) summarized some possible mechanisms that controlled the cyclicity displayed by Paradox strata. One control may have been the interaction of sedimentation and subsidence rates. Assuming constant subsidence, during times of slow sediment deposition of anhydrite and dolomite the basin would have deepened gradually. During times of more rapid deposition of halite the basin would have shoaled. A problem with this mechanism is that the rate of subsidence probably was not stable long enough to produce the thick sequence of evaporite and carbonate rocks that is present in the basin.

Another possible control was the tectonic regime of the area. Fetzner (1960, p. 1396) noted that the Uncompahgre uplift was active from Early Pennsylvanian through Permian time. His clastic ratio map of the Paradox indicated that a tremendous amount of clastic debris was shed into the basin from the Uncompahgre; this would have affected circulation of marine waters and could have caused periodic restriction of normal marine water. This mechanism alone, however, could not have caused the repeated, somewhat regular depositional cycles of evaporite facies in the basin.

Klein and Willard (1989) summarized mechanisms that caused late Paleozoic cyclothems in the central and eastern United States. They described three types of cyclothems, mainly related to the structural setting of different types of basins. One type of cyclothem is foreland-flexure dominated, in which plate-margin basins form and are filled due to collision between plates. Another end member is a marine-eustatic dominated cyclothem that occurs in basins with only moderate tectonic influence. The cyclothems in these basins are thought to be caused mainly by sea-level changes triggered by Southern Hemisphere glaciation during the Pennsylvanian.

A third type of cyclothem, a mixture of both tectonic- and eustatic-driven models, may best describe the Paradox Formation. The collision of Laurasia and Gondwana produced vertical uplift in the Uncompahgre highlands that provided a large amount of sediment influx. At the same time, the abundance of carbonates in the basin suggests that any global sea-level changes would have had a direct impact on deposition in the area.

HONAKER TRAIL FORMATION

The Honaker Trail Formation, as used in this report, follows the original definition of Wengerd and Matheny (1958), and not the definition of Baars (1962) or of Baars and others (1967) who abandoned the term Rico Formation and revised the Honaker Trail to include rocks of the type Rico. The Honaker Trail (Wengerd and Matheny, 1958, p. 2075) conformably overlies the Paradox Formation. It consists of a variable sequence of light-gray to dark-gray, finely crystalline limestone and dolomite, micaceous siltstone, and arkosic sandstone. The percentage of limestone increases at the base of the unit and toward the center of the basin, and the formation includes more clastic rocks in the upper part of the unit and along the north basin margin (Wengerd, 1957, p. 136). The clastic ratio map of Fetzner (1960, p. 1387) shows a marked increase in clastic rocks along the Uncompahgre front in the Honaker Trail Formation compared to the Paradox and Pinkerton Trail Formations. The Honaker Trail is between 800 and 1,200 ft (244–366 m) thick across much of the Reservation, although it thins abruptly to the east (fig. 14) .

The depositional setting of the Honaker Trail was an open marine basin, similar to that of the Pinkerton Trail Formation, in contrast to the restricted-basin setting of the Paradox Formation. As such, the Honaker Trail lacks the evaporite facies that is present in the Paradox. The ancestral Uncompahgre highland that bounded the north side of the Paradox basin was apparently increasingly active during deposition of Honaker Trail sediments, as indicated by greater amounts of arkosic clastic rocks in the unit along the paleomountain front. The lobate distribution of these clastic rocks (Fetzner, 1960, p. 1387) suggests deposition in fan deltas along the northeast margin of the Paradox basin.

PENNSYLVANIAN AND PERMIAN ROCKS

RICO FORMATION

The Rico Formation (Cross and Spencer, 1900, p. 59) overlies the Hermosa Group. Near Rico, Colo., the Rico Formation consists of conglomeratic sandstone and arkose interbedded with greenish-, reddish-, and

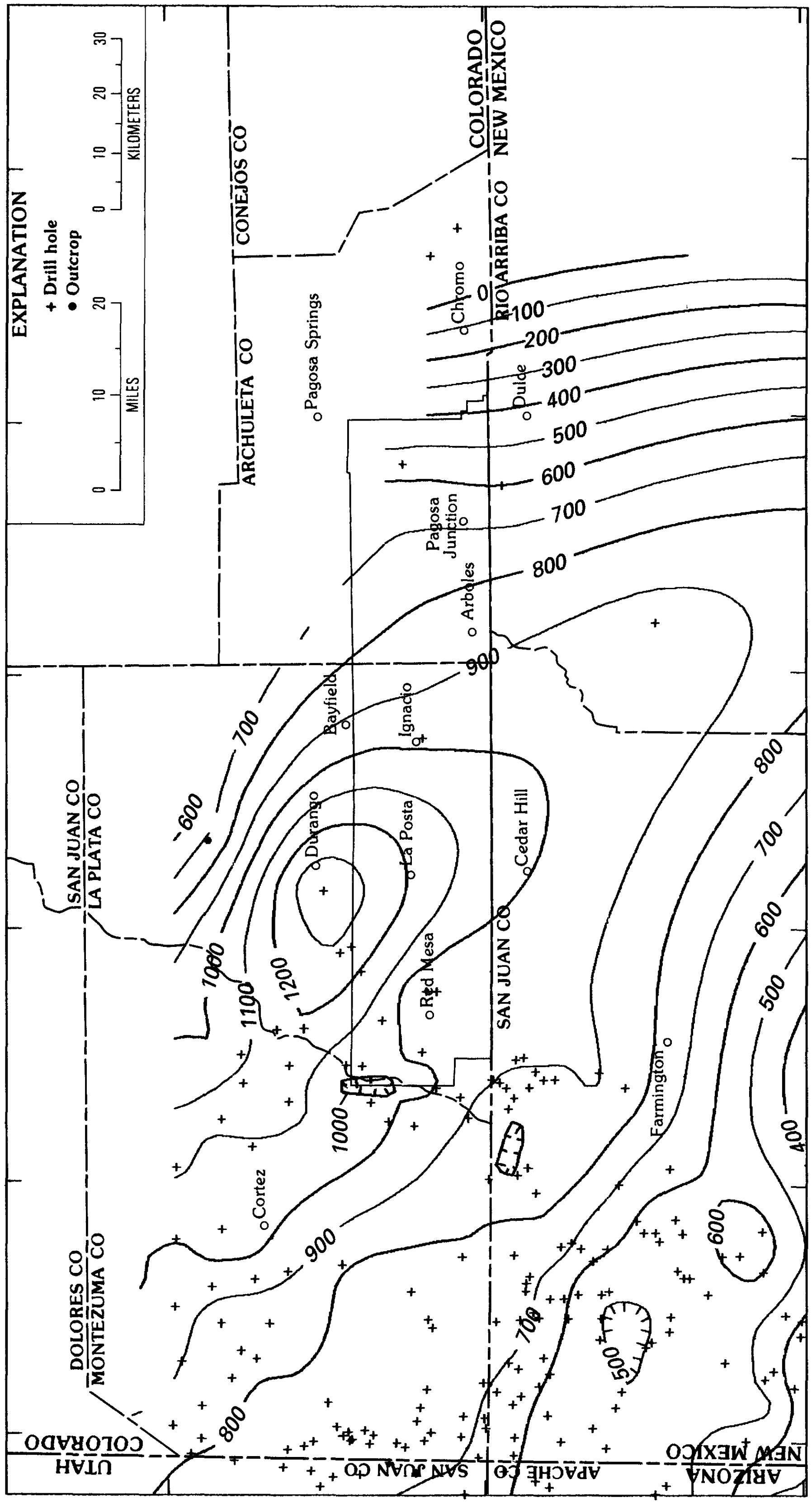

FIGURE 14.—Isopach map of the Honaker Trail Formation of the Hermosa Group. Contour interval is 100 feet. Modified from Huffman and Condon (in press).

brownish-gray shale and sandy fossiliferous limestone (Pratt, 1968, p. 85). The Rico was originally defined by Cross and Spencer (1900) on the basis of its fossil content, not by an easily mappable lithology, and its thickness was estimated to be 325 ft (99 m). It was thought to be a unit that was transitional between the underlying marine Hermosa Group and the overlying continental Cutler Group. In the area of the Reservation the Rico averages about 200 ft (61 m) in thickness (fig. 15).

Baars (1962, p. 158), Baars and Ellingson (1984, p. 17), and Pratt (1968, p. 86) have all noted the confusion that has arisen from defining a poorly exposed litho-stratigraphic unit on the basis of fossil content. Baars (1962) particularly objected to recognition of the Rico because the unit was shown to be time-transgressive. Baars (1962, p. 158) also reported a disconformity in some areas between the Hermosa Group and the Cutler Group, which would make it impossible for the Rico to be transitional between the two in those areas. However, Wengerd and Matheny (1958, p. 2080) felt that the Rico was recognizable on lithologic grounds and was a valuable guide for use in subsurface correlation. Wengerd and Matheny's (1958) cross sections included the Rico as a marker unit throughout the Four Corners region. Eckel (1968, p. 43) stated that recognition of the Rico helped in working out the structure of the La Plata dome in the La Plata Mountains (fig. 1).

For this report, most of the available geophysical logs in southwestern Colorado, southeastern Utah, northeastern Arizona, and northwestern New Mexico that include the interval in question were examined. There is definitely a rock unit, identified as the Rico on Wengerd and Matheny's (1958) cross sections, that is traceable throughout the area. This unit has a characteristic geophysical log response and is traceable from well log to well log in about the same stratigraphic position. Examination of outcrops at Rico, north of Durango, and in the Piedra River canyon has also indicated the presence of a stratigraphic interval that contains interbedded marine limestone beds similar to the underlying Hermosa and clastic beds similar to the overlying Cutler Group. Disregarding the objection that the unit is time-transgressive, as are many formations, I feel that the Rico has merit as a formation that is mappable in the subsurface, and use of the name is continued in this report. Hopefully, studies that are now underway will clarify the relationship of the Rico Formation of the San Juan Basin to the Elephant Canyon Formation of Utah.

PERMIAN ROCKS

Permian rocks in the vicinity of the Southern Ute Reservation are assigned to the Cutler Group (Cross and others, 1905, p. 5), which conformably overlies the Rico Formation. Near the Uncompahgre uplift the Cutler consists of coarse, arkosic clastic rocks and is considered to be a single undivided unit of formation rank; however, to the south and southwest of the uplift it is given group rank, and is divided into several formations that can be distinguished lithologically. These formations are, from oldest to youngest, the Halgaito, Cedar Mesa, Organ Rock, and De Chelly Sandstone. All these formations grade laterally northward and northeastward into the undivided Cutler, and contacts between the formations are gradational. Minor amounts of oil and gas have been produced from the Cutler Group in southwestern Colorado (Fassett, 1978a; 1983a), but not on the Reservation.

CUTLER FORMATION, UNDIVIDED

The undivided Cutler consists of reddish-brown to purple, fine- to medium-grained arkosic sandstone, conglomeratic sandstone, arkosic conglomerate, and minor micaceous siltstone and mudstone. A thickness of 2,500 ft (762 m) was measured on the outcrop north of Durango (Baars, 1962, p. 165); thicknesses in excess of 8,000 ft (2,438 m) have been drilled elsewhere in the Paradox basin. Across most of the Reservation the Cutler Group, including its various formations, ranges between 1,200 and 1,750 ft (366–533 m) in thickness (fig. 16). The maximum thickness of the Cutler exposed in the Piedra River area is about 850 ft (259 m); however, the Cutler is truncated by a pre-Triassic unconformity in the northern part of the Piedra River area (Steven and others, 1974; Condon and others, 1984).

Campbell (1979, 1980, 1981) interpreted the undivided Cutler as alluvial-fan deposits that were shed southward from the ancestral Uncompahgre highland and southwestward from the ancestral San Luis highland. He demonstrated a succession of four fluvial depositional assemblages: (1) proximal braided, (2) distal braided, (3) 50 percent meandering, and (4) 100 percent meandering. These facies are present mainly to the north of the Reservation. The Cutler on the Reservation consists of the formations discussed below; the distribution of each is shown separately.

CUTLER GROUP

HALGAITO FORMATION

The Halgaito Formation (Baker and Reeside, 1929, p. 1421) consists of reddish-brown to dark-brown silty

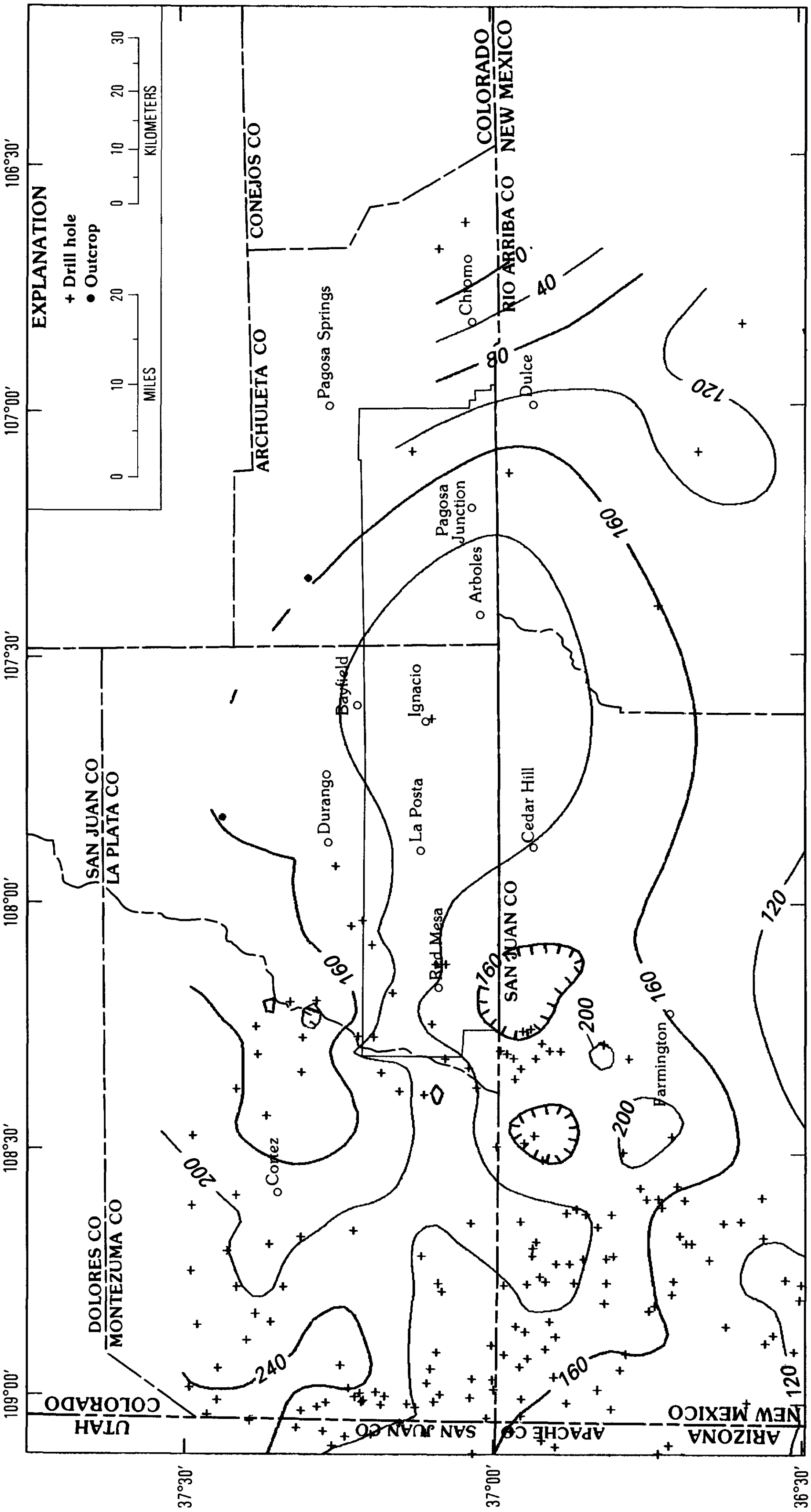

FIGURE 15.—Isopach map of the Rico Formation. Contour interval is 40 feet. Modified from Huffman and Condon (in press).

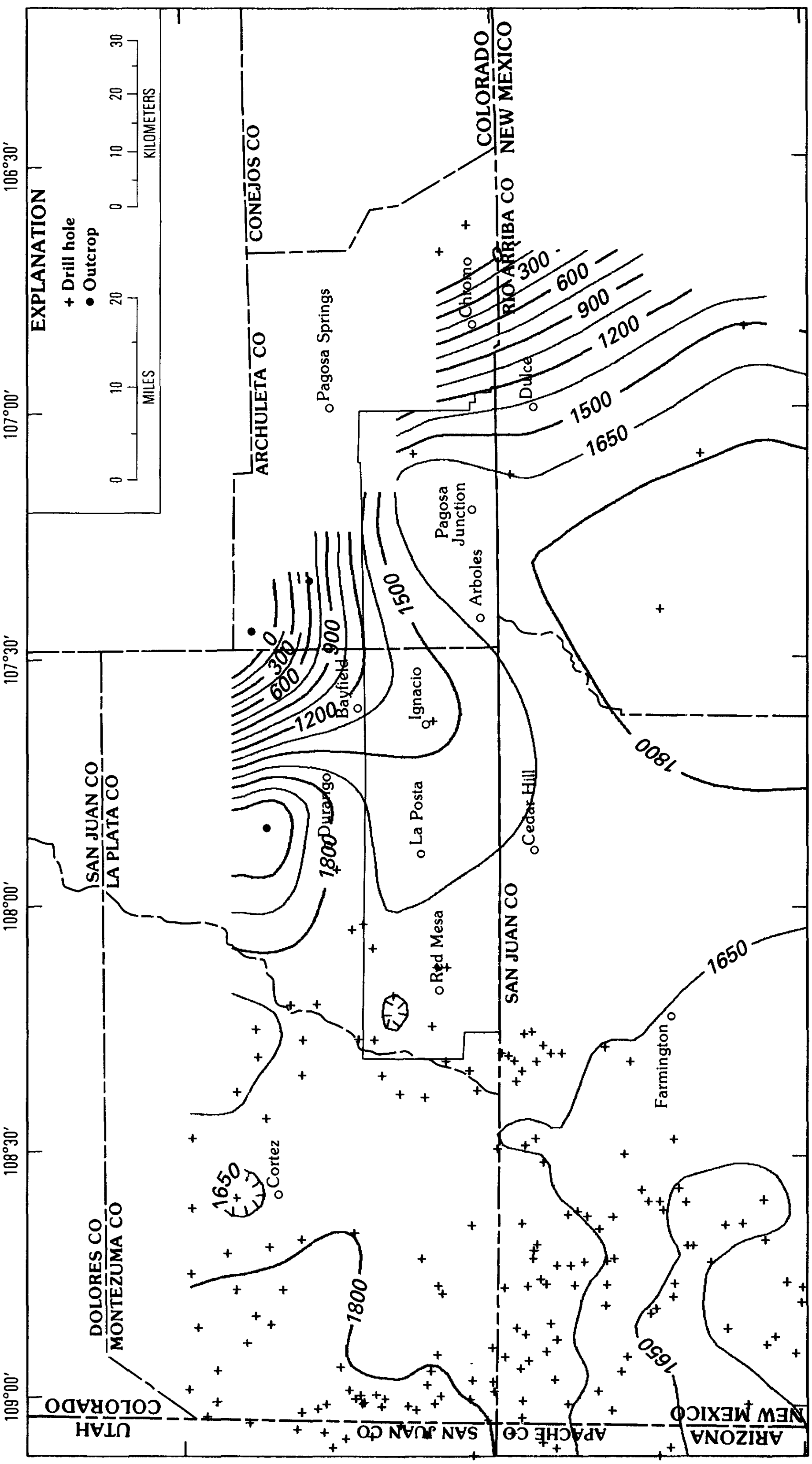

Figure 16.—Isopach map of the Cutler Group (or Formation). Contour interval is 150 feet. Modified from Huffman and Condon (in press).

sandstone and siltstone and minor gray limestone. Thin beds of sandstone and siltstone are interbedded, and outcrops consist of a series of slopes and ledges. The formation averages between 350 and 800 ft (107–244 m) in thickness on the Reservation (fig. 17). The Halgaito consists of alternating beds of marginal-marine mud-flat and fluvial sediments that were deposited near sea level (Baars, 1962, p. 169). In areas west of the Reservation significant amounts of eolian loess deposits have been found in the Halgaito (Murphy, 1987). The Halgaito conformably overlies the Rico Formation.

CEDAR MESA SANDSTONE

The Cedar Mesa Sandstone was originally described near Cedar Mesa in southeastern Utah as a thick, fine- to medium-grained sandstone (Baker and Reeside, 1929, p. 1443). Sears (1956, p. 184) and O'Sullivan (1965, p. 39) reported that the unit undergoes a facies change eastward to a sequence of pastel siltstone and shale with secondary amounts of gypsum, sandstone, and limestone near Comb Ridge, which is located about 35 mi (56 km) west of the Colorado-Utah State line. Baars (1962, p. 178) noted that this evaporitic sequence is distinctive in being pale red in contrast to the reddish-brown color of other parts of the Cutler above and below. Baars (1962) considered the Comb Ridge area as the eastern limit of recognizable Cedar Mesa; east of Comb Ridge he included the interval with the lower, undivided Cutler Group.

For this report the evaporitic facies of the Cedar Mesa was correlated in the subsurface into southwestern Colorado. Well logs were examined from Comb Ridge eastward, and the evaporitic unit was found to be traceable as a distinctive lithologic unit on the logs. Therefore, the Cedar Mesa is recognized in this report in southwestern Colorado and adjacent areas. By recognizing the Cedar Mesa in the area of the Southern Ute Reservation, it is also possible to recognize the underlying Halgaito Formation and the overlying Organ Rock Formation there. The evaporitic facies of the Cedar Mesa ranges in thickness from 150 to 350 ft (46–107 m) on the Reservation (fig. 18). The evaporite facies of the Cedar Mesa was deposited under mainly tidal-flat and sabkha conditions in Colorado and northwestern New Mexico (Stanesco and Campbell, 1989, p. F9).

ORGAN ROCK FORMATION

The Organ Rock Formation (Baker and Reeside, 1929, p. 1422) is similar to the Halgaito Formation and consists of interbedded reddish-brown to red siltstone, silty sandstone, and sandstone. Thin beds of limestone- and siltstone-pebble conglomerate are present locally near the base in areas to the west of the Reservation (O'Sullivan, 1965, p. 46). The Organ Rock Formation is 500–900 ft (152–274 m) thick across most of the Reservation (fig. 19). It contains coastal-plain, mud-flat deposits in the southern part of the area and grades northward into fluvial deposits. To the west, in Utah, the Organ Rock contains significant amounts of eolian rocks.

DE CHELLY SANDSTONE

The De Chelly Sandstone (Gregory, 1917, p. 32) is a tan, reddish-brown, and orangish-red, very fine to medium grained sandstone. The sandstone is very thick bedded and exhibits large-scale, high-angle cross-beds. The formation is as thick as 250 ft (76 m) in parts of southwestern Colorado but is from 0 to 100 ft (0–30 m) thick on the Reservation; it merges with the undivided Cutler Group near the west boundary of the Reservation (fig. 20). In some areas the De Chelly can be divided into upper and lower parts, but only the undivided unit is shown on figure 20. The De Chelly has been interpreted as an eolian deposit (Peirce, 1967).

TRIASSIC ROCKS

Triassic rocks are represented on the Southern Ute Reservation by the Dolores Formation of Late Triassic age (fig. 3). The Dolores is equivalent to part of the Chinle Formation, which is recognized in other parts of the Four Corners region (fig. 21). The Moenkopi Formation, which is present to the west and south of the Reservation, is not recognized in most parts of southwestern Colorado. In the area of the Reservation the Dolores unconformably overlies Permian rocks. This unconformity removed all Permian rocks in the Piedra River canyon area, north of the Reservation (Steven and others, 1974; Condon and others, 1984). Minor amounts of gas have been recovered from the Dolores Formation in southwestern Colorado (Irwin, 1983), but not on the Reservation.

DOLORES FORMATION

The Dolores Formation was named by Cross and Purington (1899) for exposures in the Dolores River valley, near Stoner, Colo. The Dolores is composed of interbedded red to purplish-red, very fine to coarse grained sandstone, conglomerate, siltstone, and mudstone. The unit is about 900–1,200 ft (274–366 m) thick on the west side of the Reservation (fig. 21); it is cut out

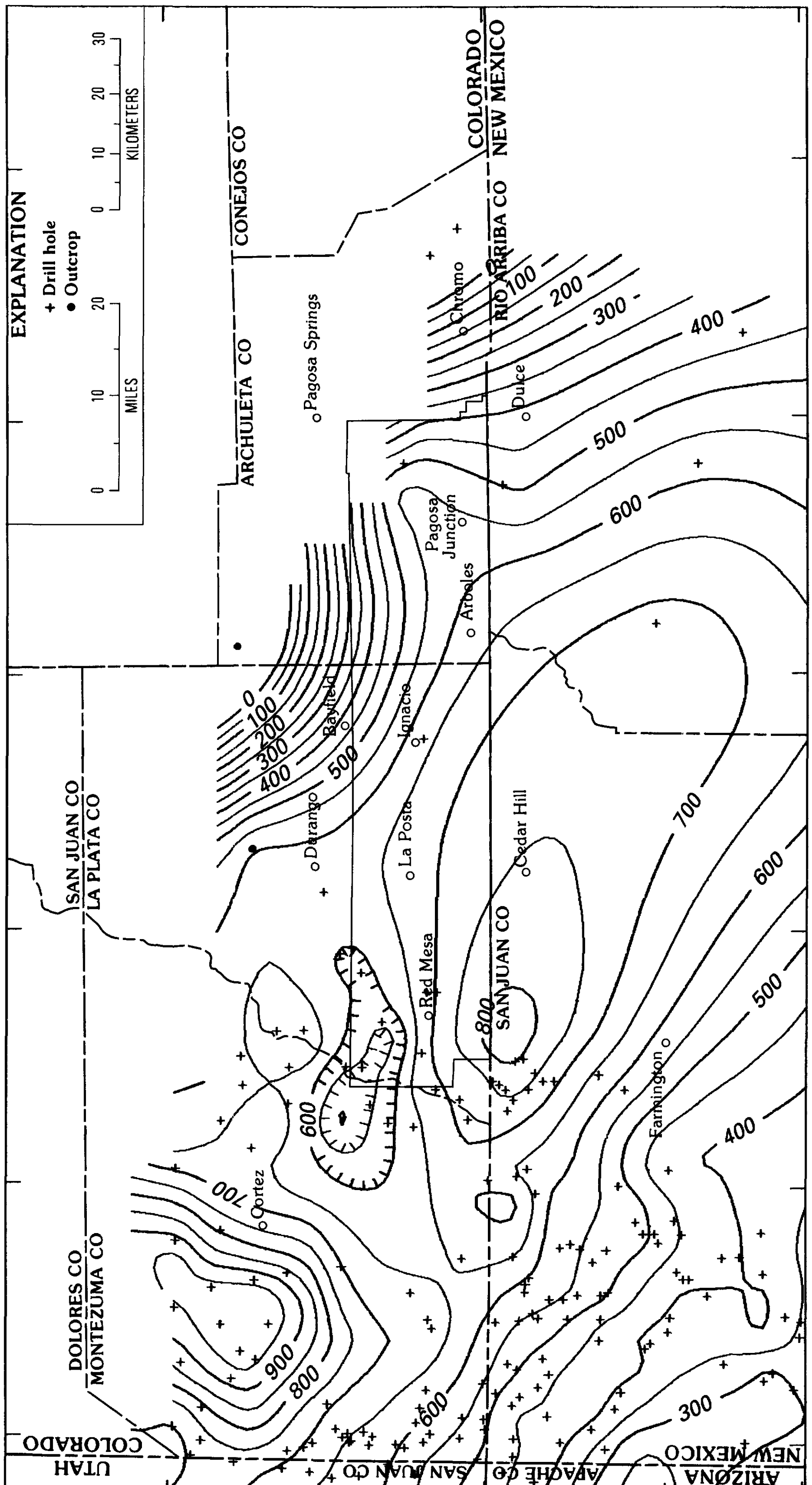

Figure 17.—Isopach map of the Halgaito Formation. Contour interval is 50 feet. Modified from Huffman and Condon (in press).

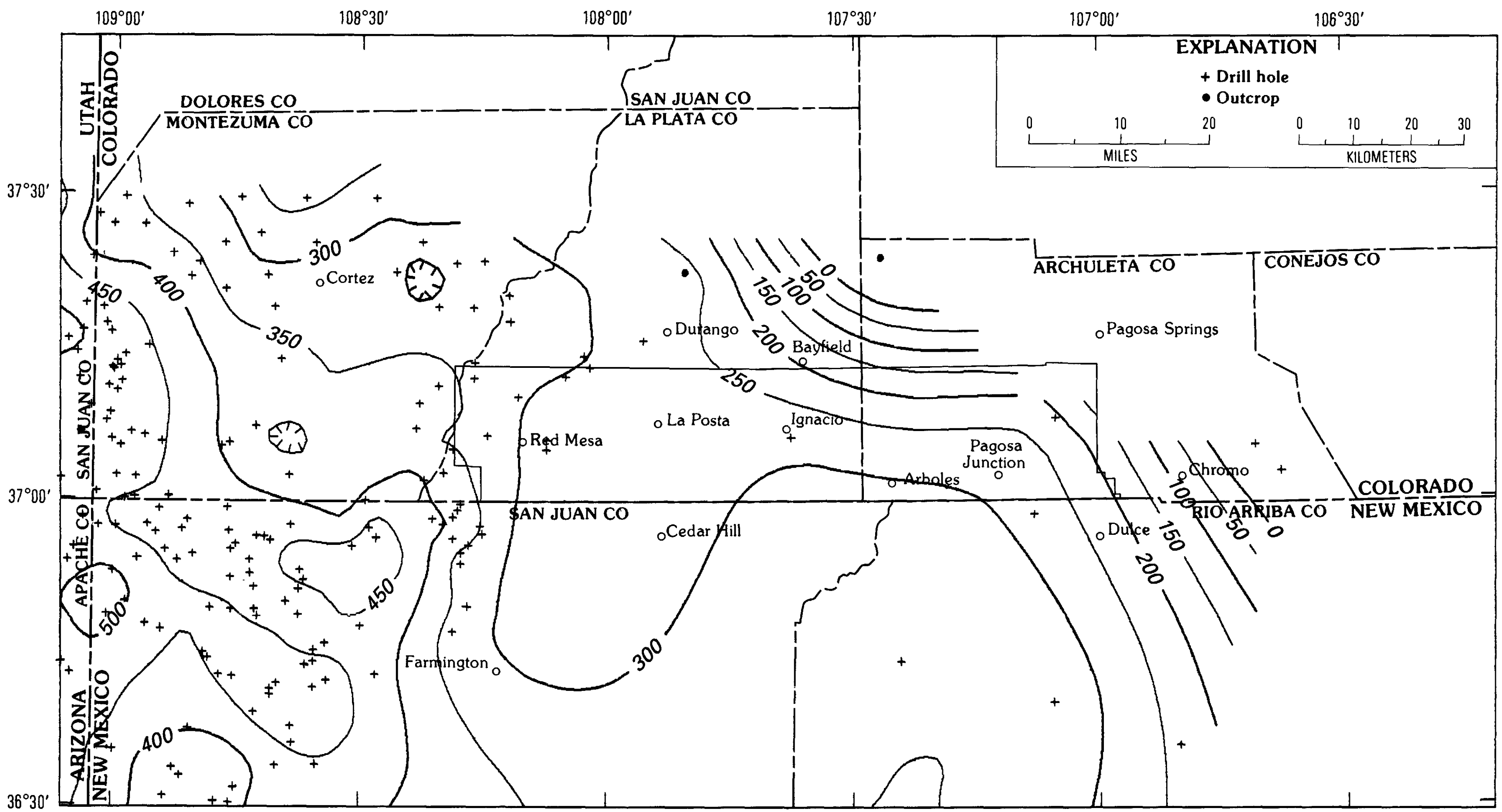

FIGURE 18.—Isopach map of the Cedar Mesa Sandstone. Contour interval is 50 feet. Modified from Huffman and Condon (in press).

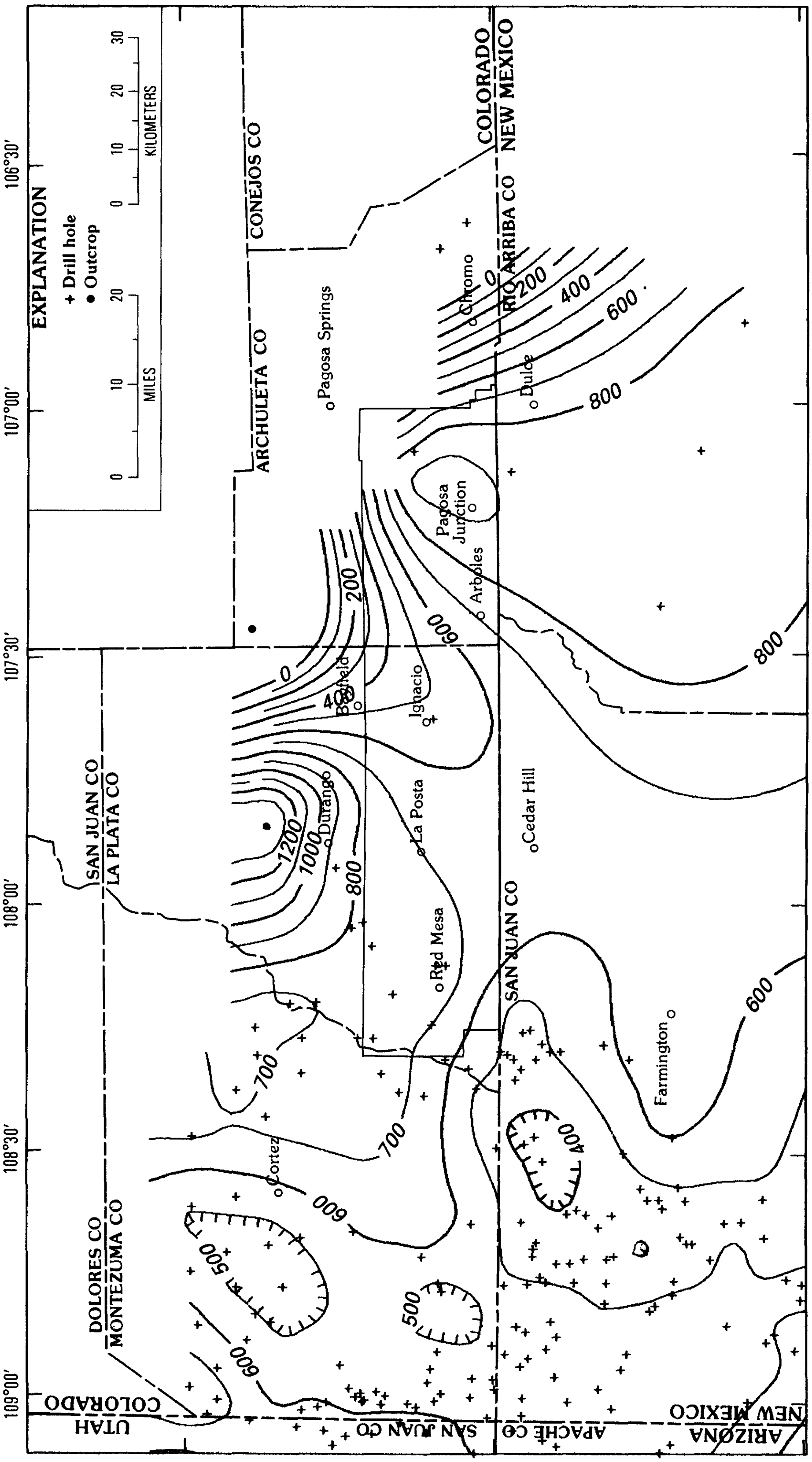

FIGURE 19.—Isopach map of the Organ Rock Formation. Contour interval is 100 feet. Modified from Huffman and Condon (in press).

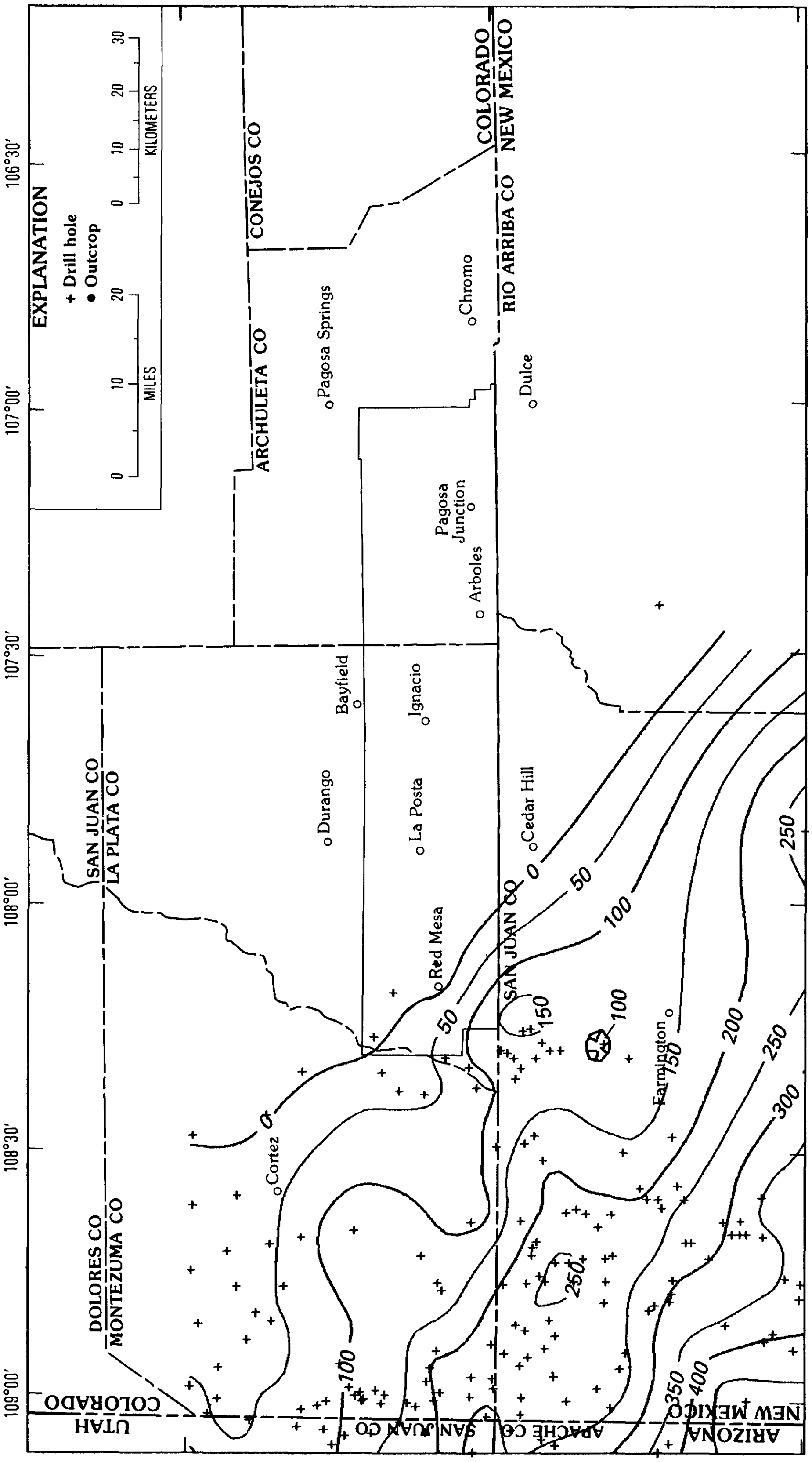

FIGURE 20.—Isopach map of the De Chelly Sandstone. Contour interval is 50 feet. Modified from Huffman and Condon (in press).

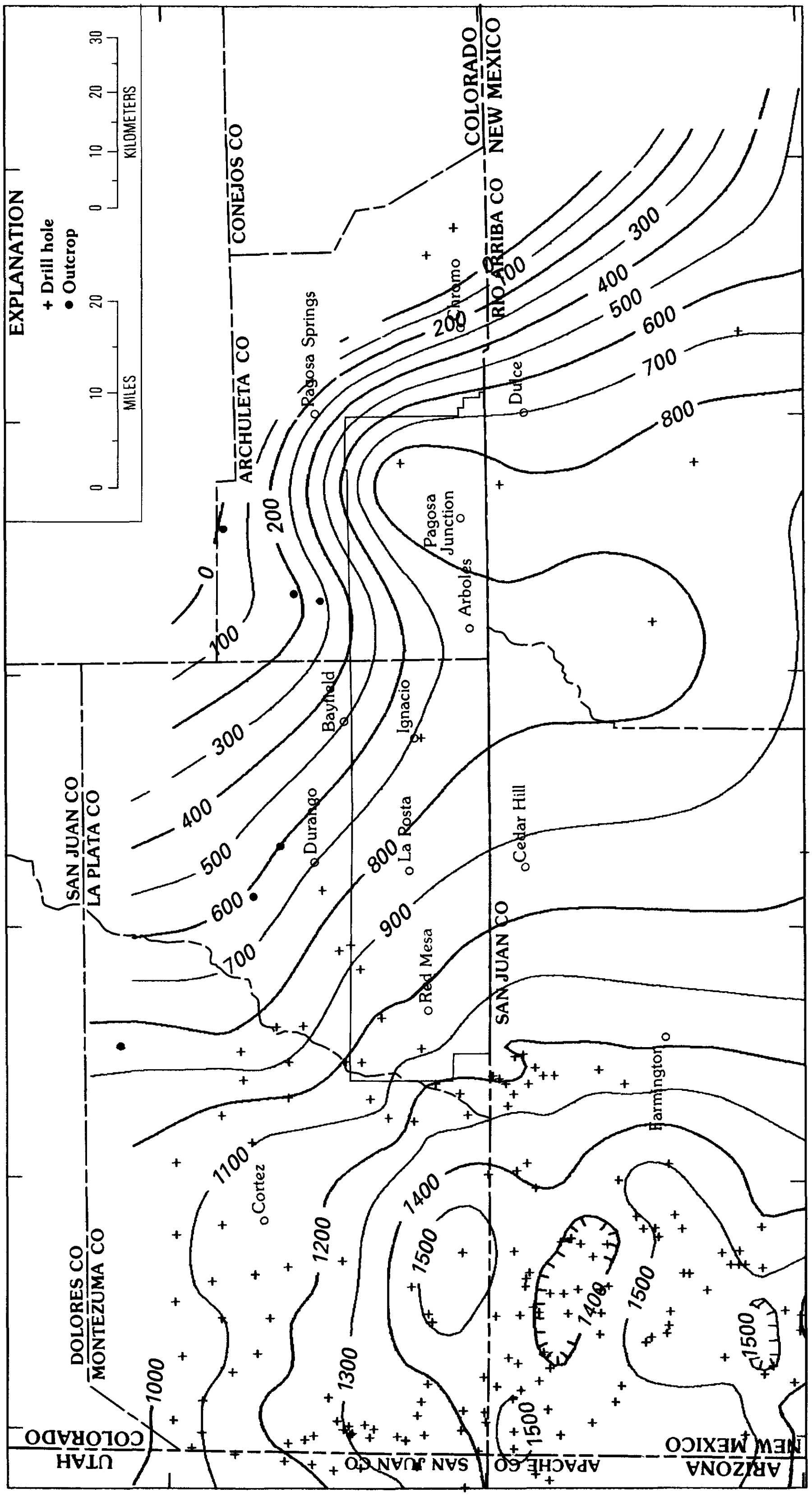

Figure 21.—Isopach map of the Dolores and Chinle Formations. Contour interval is 100 feet. Modified from unpublished data by A.C. Huffman, Jr., and S.M. Condon (1990).

in the Piedra River area by a pre-Entrada Sandstone unconformity (Read and others, 1949; Steven and others, 1974; Condon and others, 1984). Blodgett (1984, p. 48) interpreted the Dolores as fluvial-channel, floodplain, lacustrine, and eolian sand-sheet deposits.

Blodgett (1984, p. 48) noted that the Dolores is partly equivalent to the Chinle Formation of Gregory (1917) and the Wingate Sandstone of the Four Corners area. In particular, a fine-grained, massively bedded sand-sheet facies of the upper part of the Dolores is lithologically similar to, and occupies the same stratigraphic position as, the Rock Point Member of the Chinle Formation. The sand-sheet facies was examined for this report in the Dolores River valley near Stoner, Colo., on the northeast side of the La Plata Mountains at Rands Point, and at Animas City Mountain, north of Durango (fig. 1). At each location the lithology of the unit was similar to that of the Rock Point. The sand-sheet facies of the Dolores thickens and contains more crossbedded intervals in a westward direction. The unit is traceable in the subsurface in southwestern Colorado as far east as the western part of the Southern Ute Reservation, but it was not found in either outcrops or the subsurface east of Durango. The unconformity at the base of the overlying Entrada Sandstone may have removed the unit entirely in this area.

JURASSIC ROCKS

Jurassic rocks on the Southern Ute Reservation consist of the Glen Canyon Group, Entrada Sandstone, Wanakah Formation, Junction Creek Sandstone, and Morrison Formation (fig. 3). The total thickness of the Jurassic System in the area of the Reservation is 900–1,100 ft (274–305 m). The Glen Canyon Group is present only on the extreme western side of the Reservation and is thus not discussed in detail in this report.

Although some hydrocarbons have been recovered from the Entrada Sandstone in parts of northwestern New Mexico (Fassett, 1983a; Huffman, 1987), none have been produced in southwestern Colorado. Some gas has been recovered from sandstones in the upper part of the Morrison Formation in fields near the Reservation (Irwin, 1983), but not on the Reservation. The lower part of the Morrison Formation was mined for uranium ore in the Four Corners area, but these mines have been abandoned.

Jurassic rocks in the area of the Reservation are overlain by the Lower Cretaceous Burro Canyon Formation (fig. 3). This contact has been interpreted by some workers as conformable and by other workers as disconformable (Craig and Shawe, 1975, p. 164). To the south of the Reservation the Burro Canyon is cut out by an unconformity at the base of the Upper Cretaceous Dakota Sandstone; in that area the Dakota rests directly on the Morrison Formation.

GLEN CANYON GROUP

The Lower Jurassic Glen Canyon Group (Gregory and Moore, 1931; Peterson and Pipiringos, 1979) consists of the Wingate Sandstone, Kayenta Formation, and Navajo Sandstone. These three formations are difficult to distinguish as separate units, especially near the eastern pinchout of the group, hence no attempt was made to map the units separately for this report. From its eastern pinchout the group thickens abruptly westward to about 500 ft (152 m) at the Colorado-Utah State line (fig. 22). All three formations of the group are composed mainly of sandstone in Colorado. The Wingate and Navajo Sandstones are eolian units; the Kayenta is a fluvial unit.

ENTRADA SANDSTONE

The Middle Jurassic Entrada Sandstone (Gilluly and Reeside, 1928, p. 76) unconformably overlies the Dolores Formation on the eastern side of the Reservation and the Glen Canyon Group on the western side. It has been divided into two members in some parts of southwestern Colorado: the basal Dewey Bridge Member and the overlying Slick Rock Member (Wright and others, 1962). These members together range from 100 to 200 ft (30–61 m) in thickness in this area, and are shown combined on figure 23.

DEWEY BRIDGE MEMBER

The Dewey Bridge Member is composed of brick-red to reddish-brown, very fine grained, argillaceous sandstone and siltstone. It is thin to thick bedded in horizontal, slightly irregular, poorly exposed units. The thickness of the Dewey Bridge on the western side of the Reservation is 25–35 ft (8–11 m); it pinches out eastward and is not present in the Durango or Piedra River areas. The sediments of the Dewey Bridge were deposited in a sabkha environment that bordered the Jurassic sea, which was present to the north and west of Colorado (Kocurek and Dott, 1983, p. 108). The Dewey Bridge Member correlates with the Carmel Formation of Utah (Wright and others, 1962, p. 2059) and with the medial silty member of the Entrada of New Mexico and Arizona (Harshbarger and others, 1957, p. 36).

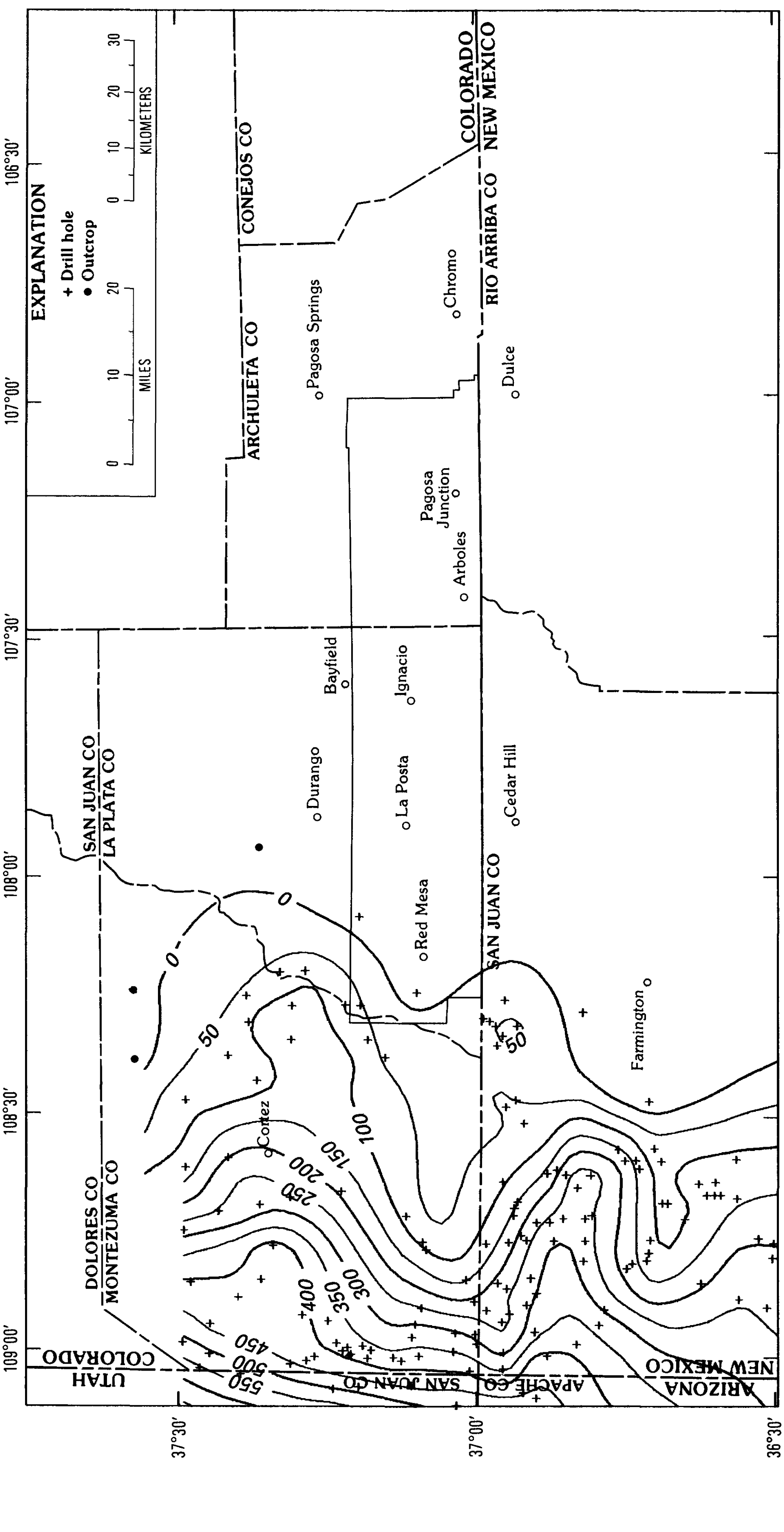

FIGURE 22.—Isopach map of the Glen Canyon Group. Contour interval is 50 feet. Modified from unpublished data by A.C. Huffman, Jr., and S.M. Condon (1990).

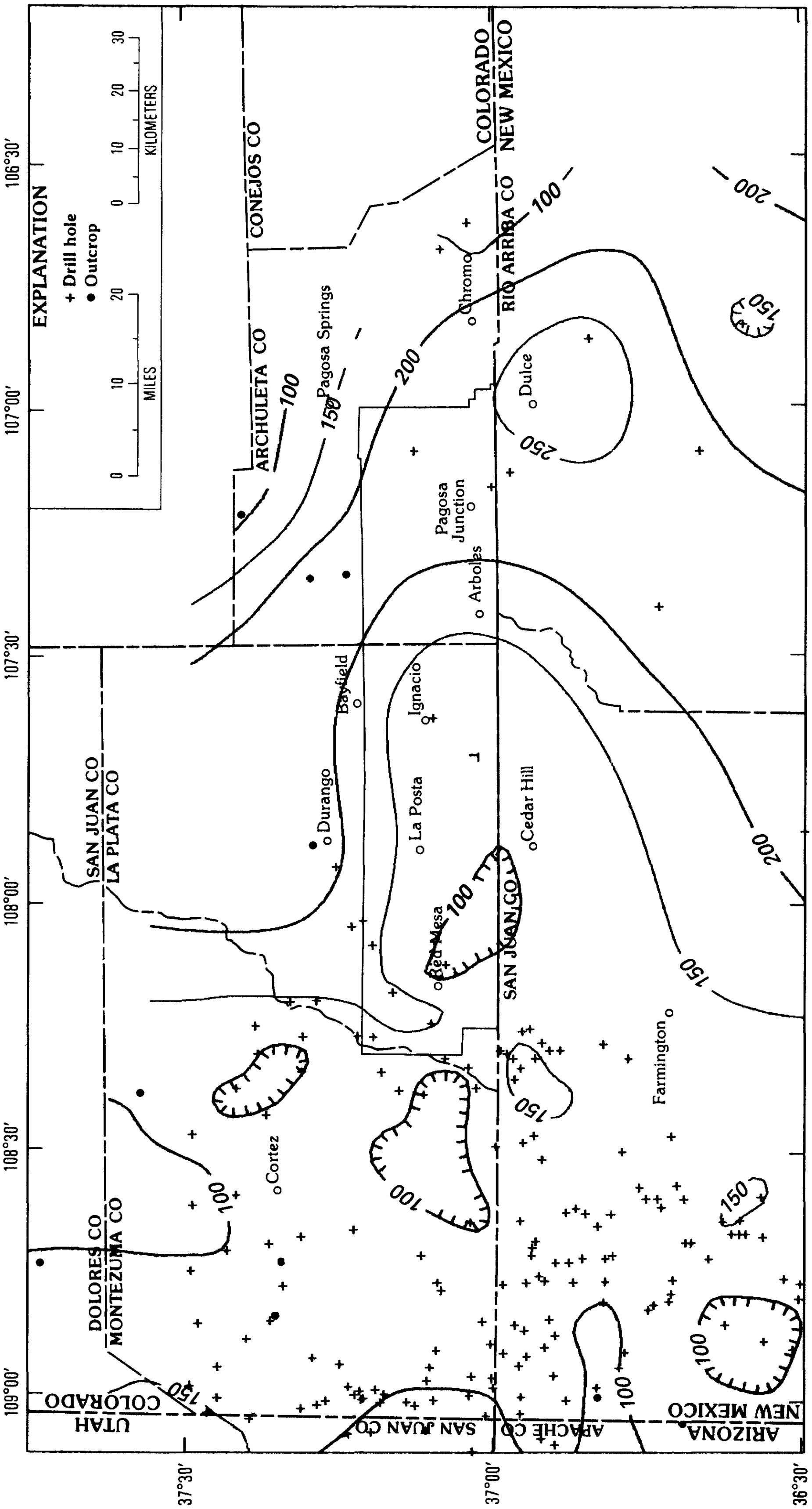

FIGURE 23.—Isopach map of the Entrada Sandstone. Contour interval is 50 feet. Modified from unpublished data by A.C. Huffman, Jr., and S.M. Condon (1990).

SLICK ROCK MEMBER

The Slick Rock Member consists of white, pinkish-orange, and reddish-orange, very fine to fine grained, locally medium grained sandstone. Bedding is medium to thick with alternating cosets of crossbedded and flat-bedded strata. The lower part of the member is reddish brown and is more argillaceous or earthy than the upper part. The Slick Rock averages 70–100 ft (21–30 m) in thickness in the subsurface in the area of this report; it thickens to as much as 250 ft (76 m) to the north in the Piedra River area. The sediments of the Slick Rock were deposited in an extensive area of eolian dunes and interdunes that bordered the Jurassic sea, which was present to the north and west of Colorado (Kocurek and Dott, 1983, p. 110). The Slick Rock Member correlates with the upper sandy member of the Entrada of New Mexico and Arizona (Harshbarger and others, 1957, p. 36).

WANAKAH FORMATION

The Middle Jurassic Wanakah Formation (Burbank, 1930, p. 172), which conformably overlies the Entrada Sandstone, is divided into three members in New Mexico and Arizona (Condon and Huffman, 1988). From oldest to youngest these are the Todilto Limestone Member, Beclabito Member, and Horse Mesa Member. These members were traced in the subsurface from New Mexico to southwestern Colorado; the New Mexico nomenclature is used here for convenience with the qualification "and equivalent rocks" and to simplify the regional correlations. Eckel (1949, 1968) applied different member names—Pony Express Limestone Member (at the base), Bilk Creek Sandstone Member, and upper member—to the Wanakah in the La Plata Mountains area (fig. 1). Many use the Burbank (1930), Goldman and Spencer (1941) and Eckel (1949, 1968) nomenclature in southwestern Colorado. As presently interpreted by A.C. Huffman, Jr., and S.M. Condon, the Bilk Creek Sandstone Member and the upper member are equivalent to the Beclabito Member. A unit that forms the basal part of the overlying Junction Creek Sandstone equivalent to the Horse Mesa Member is included with Horse Mesa on figure 26.

TODILTO LIMESTONE MEMBER AND EQUIVALENT ROCKS

The Todilto Limestone Member consists of light-gray to dark-gray, thinly laminated to massive limestone. A characteristic feature of the limestone, when broken, is a fetid odor. Analysis of two samples of the unit by Franczyk and others (1985) indicated organic-carbon contents of less than 1 percent. The limestone is as thick as 120 ft (37 m) in the southeastern part of the Reservation and pinches out in the subsurface west of the Reservation (fig. 24). The unit is about 15 ft (4.5 m) thick in the Piedra River area. The sediments of the Todilto were deposited in a large, restricted-marine basin. The Todilto contains substantial amounts of anhydrite and gypsum farther south in New Mexico. Some exposures of the member in the Piedra River area contain a limestone-gypsum breccia at the top (Condon and others, 1984).

BECLABITO MEMBER AND EQUIVALENT ROCKS

The Beclabito Member conformably overlies the Todilto Limestone Member or, in areas beyond the pinchout of the Todilto, the Entrada Sandstone. The Beclabito is an assemblage of interbedded reddish-orange to reddish-brown claystone, siltstone, silty sandstone, and fine-grained sandstone. Bedding is thin to medium in laterally extensive, horizontal cosets. The Beclabito is about 80 ft (24 m) thick in the subsurface in the western part of the Reservation (fig. 25) and thickens to about 100 ft (30 m) in the central and eastern parts. The sediments of the Beclabito were deposited in marginal-marine and sabkha environments (Condon and Huffman, 1988). In the La Plata Mountains, Eckel (1968, p. 45) recognized a sandstone member just above the Pony Express Limestone that he called the Bilk Creek Sandstone Member. The Bilk Creek was not distinctive on geophysical logs in the report area and is not evident at the surface in the Piedra River area.

HORSE MESA MEMBER AND EQUIVALENT ROCKS

The Horse Mesa Member conformably overlies the Beclabito Member. The Horse Mesa is composed of pale-red to reddish-brown, fine- to medium-grained sandstone. Coarse grains of white chert are locally abundant. The member is medium to very thick bedded and has alternating flat-bedded and crossbedded cosets. In the subsurface the Horse Mesa has a distinctive geophysical log response and is 40 ft (12 m) thick or less across much of the Reservation (fig. 26). It is not recognizable as a separate unit at outcrops in the Piedra River area. The sediments of the Horse Mesa were deposited in eolian dune and interdune environments (Condon and Huffman, 1988). Southeast of the Reservation in New Mexico, Ridgley (1989) interpreted the upper part of the Wanakah Formation as lacustrine in origin on the basis of nonmarine mollusks.

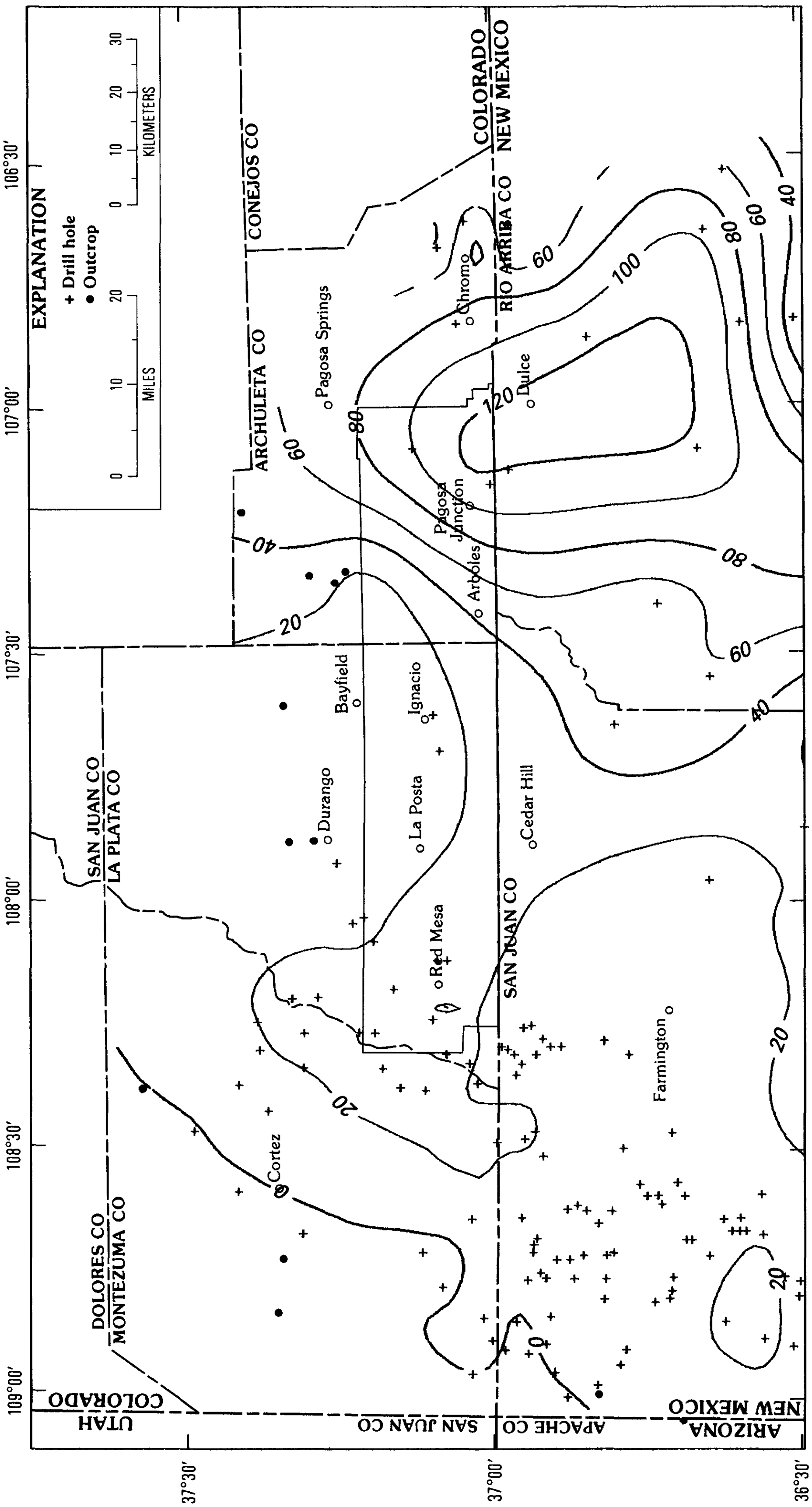

FIGURE 24.—Isopach map of the Todilto Limestone Member of the Wanakah Formation and equivalent rocks. Contour interval is 20 feet. Modified from unpublished data by A.C. Huffman, Jr., and S.M. Condon (1990).

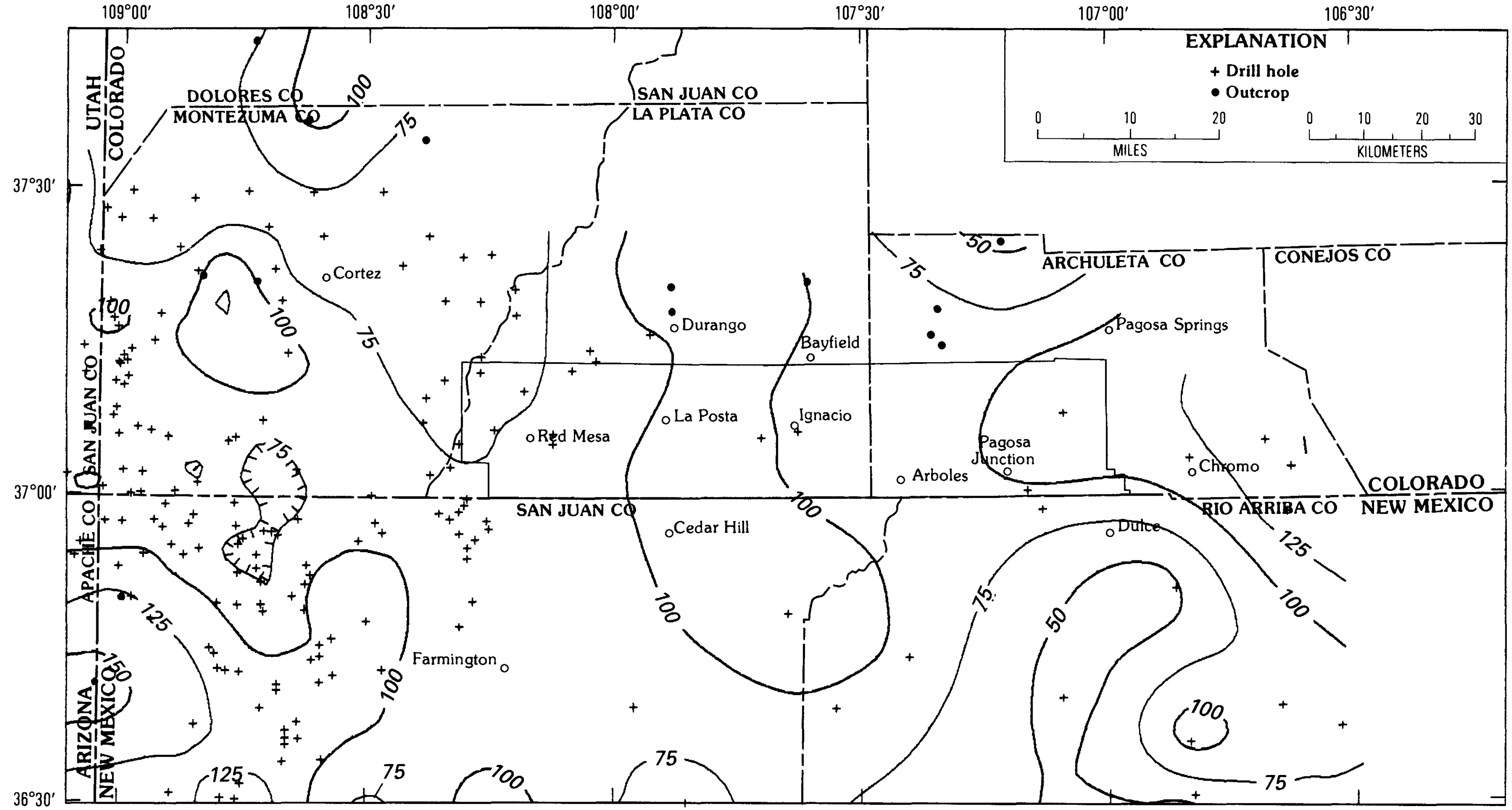

Figure 25.—Isopach map of the Beclabito Member of the Wanakah Formation and equivalent rocks. Contour interval is 25 feet. Modified from unpublished data by A.C. Huffman, Jr., and S.M. Condon (1990).

JUNCTION CREEK SANDSTONE

The Jurassic Junction Creek Sandstone (Goldman and Spencer, 1941) overlies the Wanakah Formation. The Junction Creek was informally divided into three units in southwesternmost Colorado by Ekren and Houser (1965, p. 12). The lower unit is reddish-orange to brown, fine- to medium-grained sandstone. Bedding is medium to thick and consists of alternating flat-bedded and crossbedded cosets. Laterally extensive horizontal bedding planes are characteristic of this unit. The lower unit was described as about 40 ft (12 m) thick by Ekren and Houser (1965, p. 13).

Outcrop and subsurface studies indicate that the lower unit of the Junction Creek is equivalent to the Horse Mesa Member of the Wanakah Formation (A.C. Huffman, Jr., and S.M. Condon, unpublished data, 1990). The isopach map of the Junction Creek (fig. 27) excludes the lower unit, which is mapped with the Horse Mesa Member of the Wanakah (fig. 26).

The middle unit of the Junction Creek, as described by Ekren and Houser (1965) consists of pink to orange, fine- to medium-grained sandstone. Coarse grains and granules of chert are commonly concentrated on bedding planes. The middle unit is thick to very thick bedded and has very large scale crossbedded cosets. The unit is about 250 ft (76 m) thick in McElmo Canyon and generally thins eastward in the subsurface; it attains a thickness of nearly 300 ft (91 m) in the Mesa Verde area southeast of Cortez, Colo. (fig. 27). The upper unit is grayish-red, fine-grained, argillaceous sandstone. Bedding is thin to medium in horizontal, flat-bedded units. The thickness of the upper unit is variable; 30 ft (9 m) was measured by Ekren and Houser (1965, p. 12) in McElmo Canyon. The middle and upper units of the Junction Creek thin to 100 ft (30 m) or less at the surface in the Piedra River area. The sediments of the middle and upper units of the Junction Creek were deposited in eolian environments, which varied from dune to interdune-playa (Peterson and Turner-Peterson, 1987, p. 8).

The middle and upper units of the Junction Creek Sandstone are equivalent to the Bluff Sandstone Member of the Morrison Formation, which is recognized in Utah, Arizona, and New Mexico. Use of the dual nomenclature is unfortunate, but arose before extensive exploration for oil and gas provided a network of well logs with which to conduct subsurface correlations. Other units, such as the Chinle and Dolores, members of the Entrada Sandstone, and members of the Wanakah Formation are also burdened with dual nomenclature, but it should be remembered that the lithologic units remain the same, even though the nomenclature changes at the State lines.

MORRISON FORMATION

The Upper Jurassic Morrison Formation (Eldridge, 1896, p. 60) was divided into several members in the Four Corners area by Gregory (1938). On the Reservation these are, from oldest to youngest, the Salt Wash, Recapture, Westwater Canyon, and Brushy Basin Members. As noted above, in other areas the Bluff Sandstone Member, which is equivalent to the middle and upper units of the Junction Creek Sandstone, is also recognized as a member of the Morrison.

In the Four Corners area the Recapture can be easily distinguished from the underlying Salt Wash Member and the overlying Westwater Canyon Member. There the Recapture consists of a reddish-brown, mudstone-dominated, fluvial unit that contrasts with the more massive, light-gray sandstone-dominated Salt Wash and Westwater Canyon Members. An attempt has been made to trace the mudstone unit eastward into the Reservation area in the subsurface, but the Salt Wash and Westwater Canyon Members also become increasingly mudstone dominated in an eastward direction, which makes distinction of the members difficult. The isopach maps of the three members are a best guess of the thicknesses and distribution of the units using the limited subsurface data available.

SALT WASH MEMBER

The Salt Wash Member is light-gray, yellow, and tan, fine- to medium-grained sandstone and greenish-gray to reddish-brown mudstone. The sandstone occurs in lenticular, but fairly extensive, crossbedded units. A lower, slope-forming unit, which is as thick as 50 ft (15 m), may be equivalent to the Tidwell Member of Peterson (1988). The Salt Wash averages between 100 and 150 ft (30–46 m) in thickness across most of the Reservation (fig. 28). The sediments of the Salt Wash were deposited as part of an extensive alluvial complex, which was composed of sediments shed from highlands to the west (Craig and others, 1955, p. 125; Peterson and Turner-Peterson, 1987, p. 8).

RECAPTURE MEMBER

The Recapture is white to light-gray, fine-grained sandstone and reddish-brown to pale-green mudstone. It conformably overlies the Salt Wash Member in most of the mapped area (fig. 29), except in the area north of the Reservation, where the Recapture is not recognized, and southeast of Dulce, N. Mex., where the Recapture overlies either the Bluff Sandstone Member or the Horse Mesa Member of the Wanakah Formation. The Recapture is about 50–100 ft (15–30 m) thick on

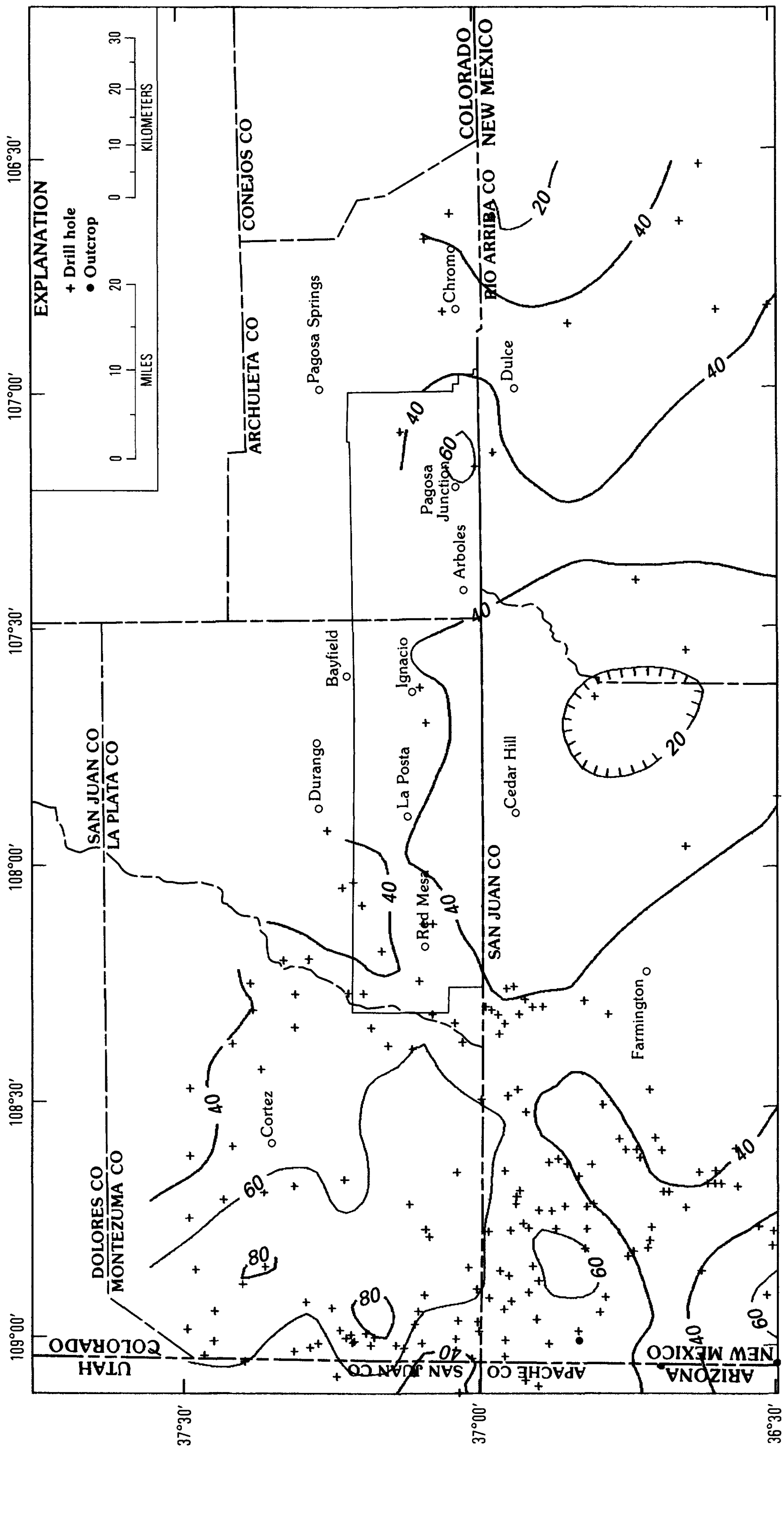

FIGURE 26.—Isopach map of the Horse Mesa Member of the Wanakah Formation and equivalent rocks. Contour interval is 20 feet. Modified from unpublished data by A.C. Huffman, Jr., and S.M. Condon (1990).

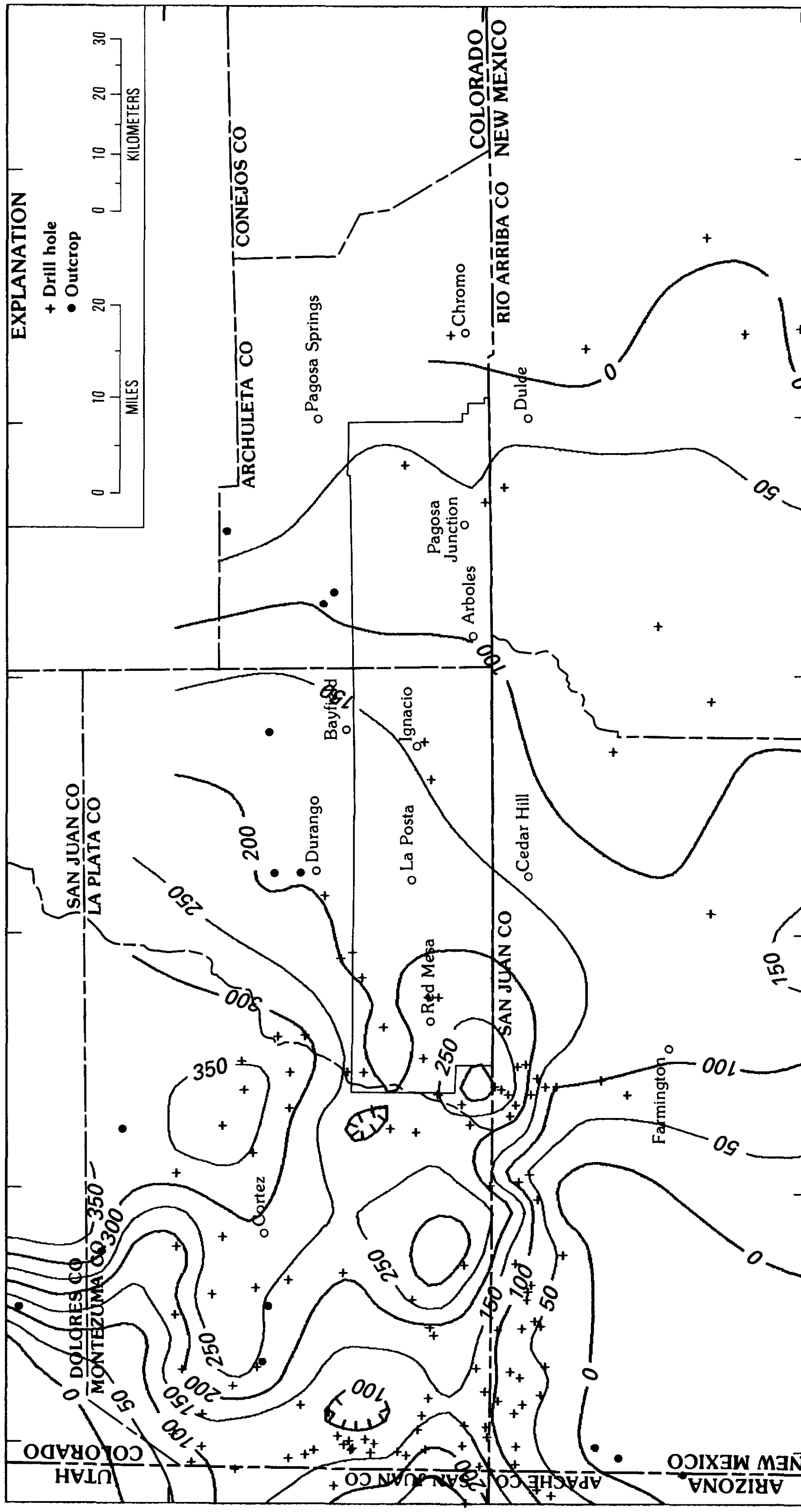

FIGURE 27.—Isopach map of the middle and upper units of Junction Creek Sandstone and equivalent rocks. Contour interval is 50 feet. Modified from unpublished data by A.C. Huffman, Jr., and S.M. Condon (1990).

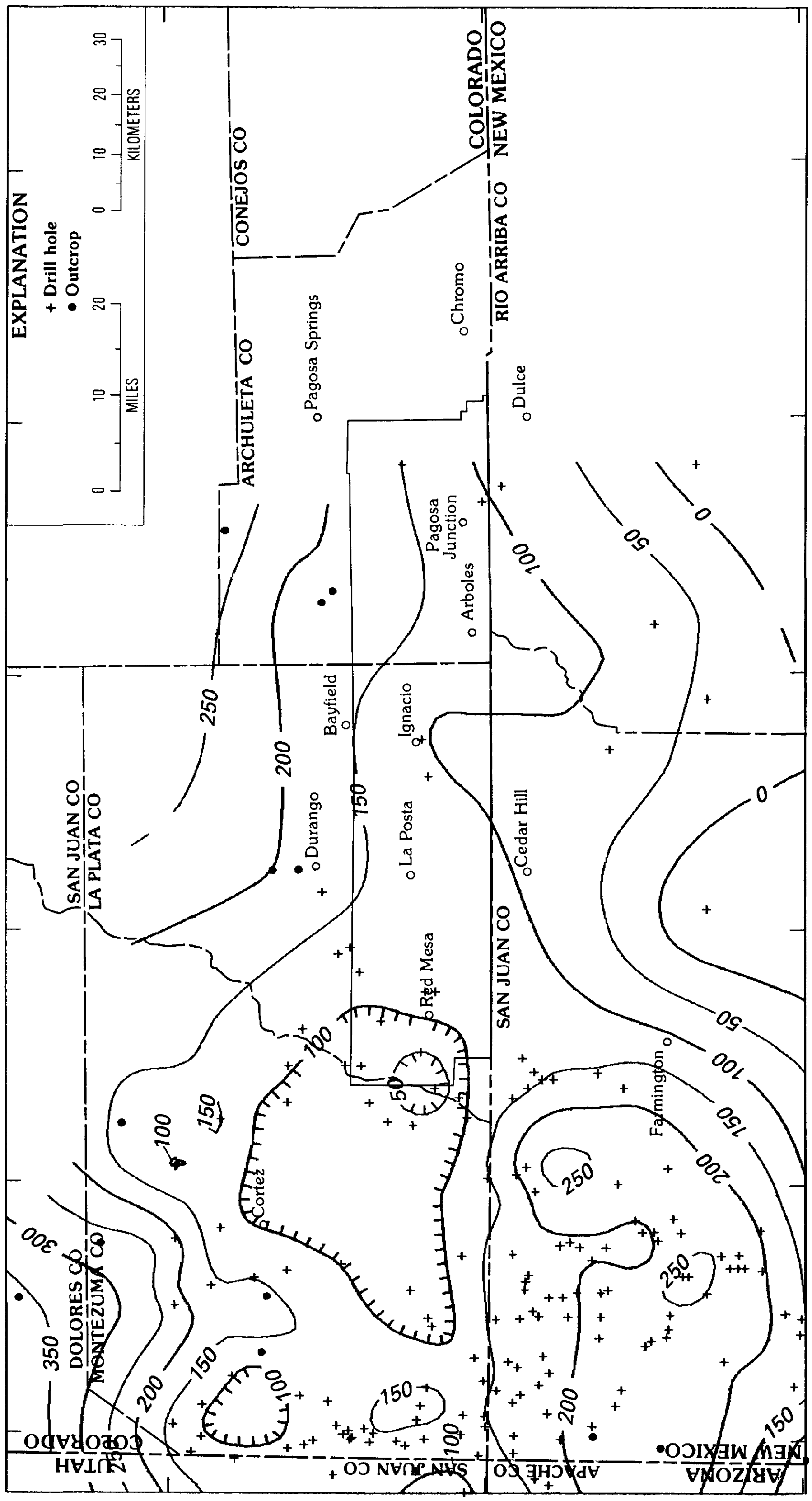

FIGURE 28.—Isopach map of the Salt Wash Member of the Morrison Formation. Contour interval is 50 feet. Modified from unpublished data by A.C. Huffman, Jr., and S.M. Condon (1990).

the Reservation (fig. 29). It is a fluvial unit (Peterson and Turner-Peterson, 1987, p. 9) in the area of the Reservation.

WESTWATER CANYON MEMBER

The Westwater Canyon Member conformably overlies the Recapture Member. The Westwater Canyon is tan, light-gray, and yellowish-brown, fine- to medium-grained, crossbedded sandstone and light greenish-gray to dark-gray mudstone. The member is 0–160 ft (0–49 m) thick on the Reservation (fig. 30). The sediments of the Westwater Canyon were deposited as part of an alluvial complex that prograded from a source area southwest of Colorado (Craig and others, 1955, p. 126; Turner-Peterson, 1985, p. 2002; Peterson and Turner-Peterson, 1987, p. 11).

BRUSHY BASIN MEMBER

The Brushy Basin Member conformably overlies the Westwater Canyon Member and consists of light-greenish-gray to reddish-brown, smectitic mudstone; very fine grained sandstone; and minor amounts of conglomeratic sandstone, limestone, and the zeolites analcime and clinoptilolite. The Brushy Basin is less than 200 ft (61 m) thick across much of the Reservation (fig. 31) but thickens to more 300 ft (91 m) in the Piedra River area. The Brushy Basin has a fluvial and lacustrine origin (Turner-Peterson, 1985, p. 2003; Turner-Peterson and Fishman, 1986; Peterson and Turner-Peterson, 1987, p. 12).

GEOLOGIC HISTORY

Deposition of Phanerozoic sediments began in Late Cambrian time with deposition of the sands of the Ignacio Quartzite. This unit was deposited in subaerial, littoral, and upper-neritic environments on the shallow shelf that bounded the western side of the craton (Baars and See, 1968, p. 337). Deposition of this unit was controlled to a large extent by Paleozoic fault blocks (Stevenson and Baars, 1986). The Four Corners region was then slightly uplifted and eroded in the interval between Late Cambrian and Late Devonian time. A system of horsts and grabens formed, probably inherited from Precambrian fault-block patterns, which selectively preserved the Ignacio in the downthrown blocks (Stevenson and Baars, 1986).

Upper Devonian through Mississippian rocks are an assemblage of limestone, dolomite, sandstone, and shale that continued to form on a shallow craton-edge shelf. Armstrong and Holcomb (1989, p. D4) showed an unconformity within this interval between the Ouray and Leadville Limestones. This unconformity apparently was not accompanied by significant tectonic activity in this area, because the Ouray Limestone was not selectively removed or preserved in local areas. The erosion that resulted in the unconformity at the top of the Leadville Limestone had a much greater impact on the distribution of Mississippian and older Paleozoic rocks by removing them entirely in some areas.

The rise of the ancestral Uncompahgre and San Luis highlands and the simultaneous development of the Paradox basin during Pennsylvanian time had a major impact on sedimentation in this area. Coarse arkosic sediments were deposited on the northeastern side of the basin, whereas carbonate sediments were deposited on the shelves and in the central basin. The development of porous carbonate algal mounds, organic-rich shale source beds, and interbedded non-porous anhydrite at this time produced the ingredients for future formation of important oil and gas reserves. During times of periodic isolation the Paradox basin did not receive an influx of normal marine water. At these times thick deposits of halite, anhydrite, and other evaporite minerals accumulated in the central basin. The Uncompahgre highlands continued to rise and influence sedimentation during Permian time, and they provided the abundant coarse arkosic sediments of the Cutler north of the Reservation. Winnowing of these sediments by wind and water resulted in the several formations of the Cutler Group on the Reservation.

A major unconformity developed prior to deposition of the sediments of the Triassic Dolores Formation as indicated by the absence of Lower and Middle Triassic rocks in the area. The Dolores and correlative Chinle Formations were formed in a large alluvial basin that included all the San Juan Basin and areas to the west. The Dolores received some clastic sediments from the ancestral Uncompahgre highland, but major sediment sources were farther to the northeast and east (Blakey and Gubitosa, 1983, p. 59).

Post-Late Triassic to Early Jurassic regional uplift and erosion are recorded by unconformities below the Lower Jurassic Glen Canyon Group and below the Middle Jurassic Entrada Sandstone. These regional unconformities extend throughout the Colorado Plateau (Pipiringos and O'Sullivan, 1978). In the Piedra River area the Entrada overlies many different rock units, which range from Triassic to Proterozoic in age; this is evidence of significant pre-Entrada structural movement.

Major tectonic events did not greatly affect Middle Jurassic deposition in the Reservation area. Local tectonism affected facies distribution, but substantial

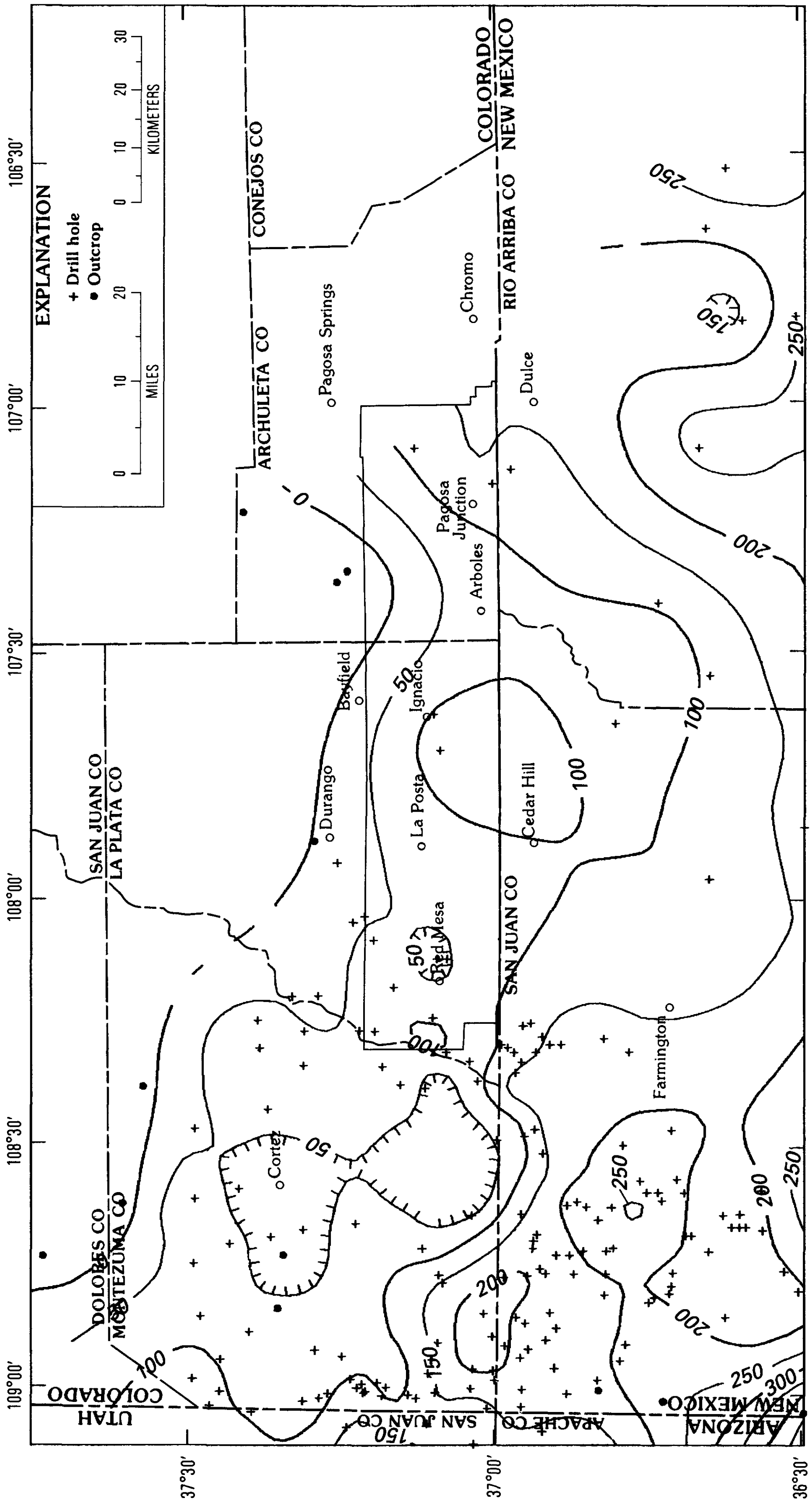

FIGURE 29.—Isopach map of the Recapture Member of the Morrison Formation. Contour interval is 50 feet. Modified from unpublished data by A.C. Huffman, Jr., and S.M. Condon (1990).

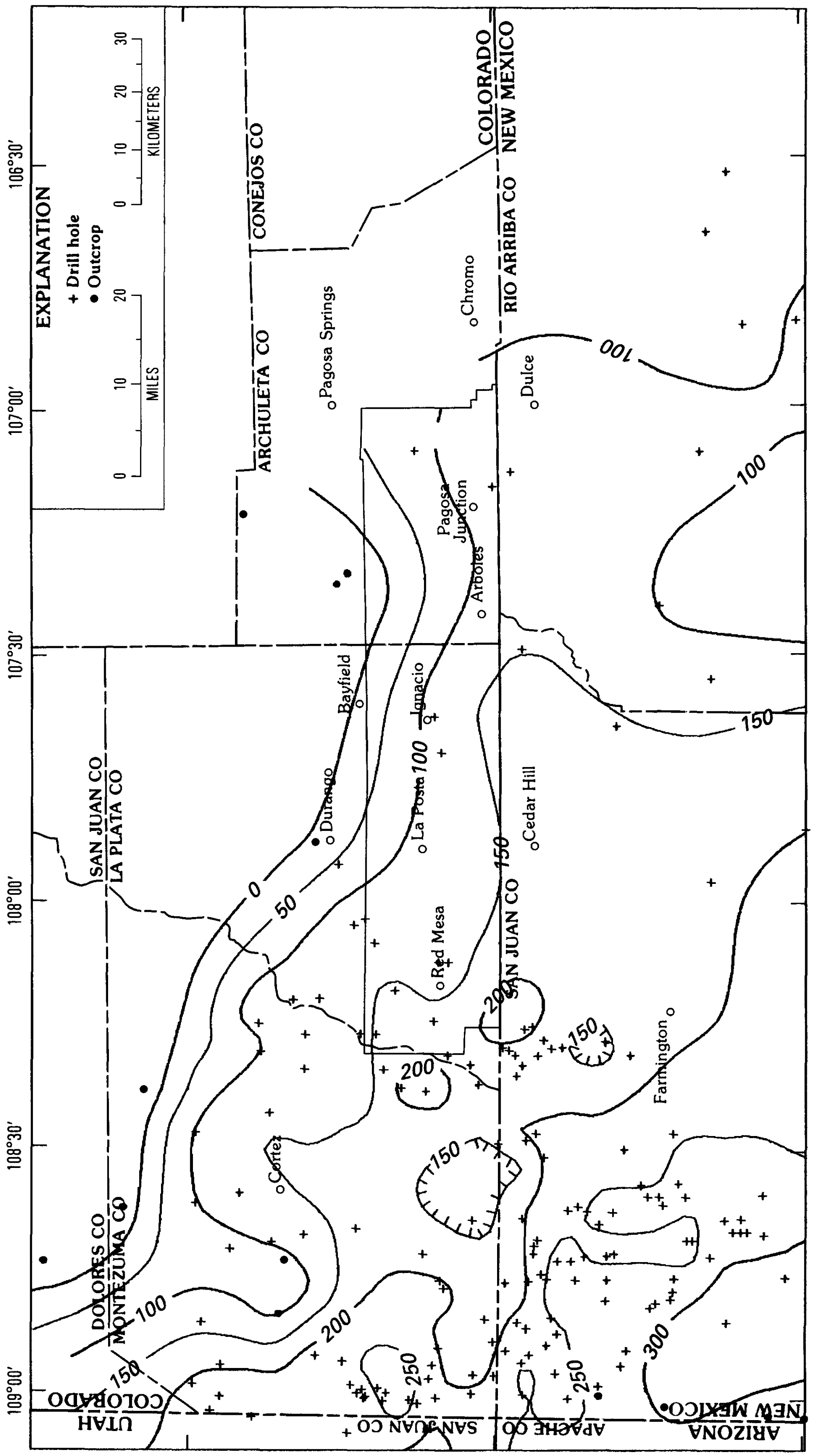

FIGURE 30.—Isopach map of the Westwater Canyon Member of the Morrison Formation. Contour interval is 50 feet. Modified from unpublished data by A.C. Huffman, Jr., and S.M. Condon (1990).

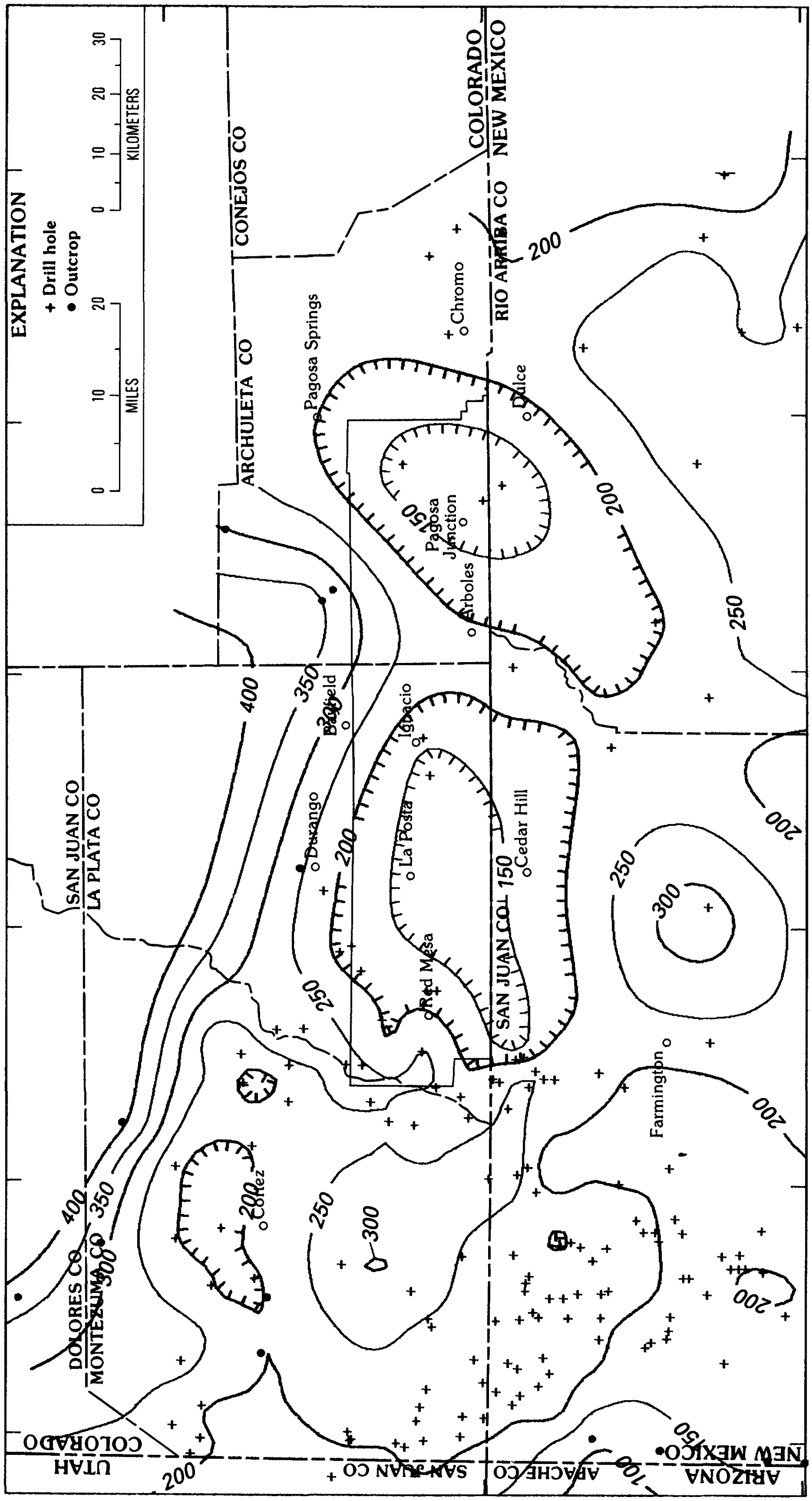

FIGURE 31.—Isopach map of the Brushy Basin Member of the Morrison Formation. Contour interval is 50 feet. Modified from unpublished data by A.C. Huffman, Jr., and S.M. Condon (1990).

tectonic influences from outside the area were not evident until the sediments of the Upper Jurassic Morrison Formation were deposited. The Morrison has been interpreted as being the result of deposition mainly by streams flowing to the east and northeast from an island-arc complex that was located along the west margin of the continent (Kocurek and Dott, 1983, p. 112). Prior to development of the stream system, significant eolian deposition occurred in the Junction Creek Sandstone and equivalent rocks in the lower part of the Morrison.

SUMMARY

Through much of the Paleozoic and Mesozoic the Southern Ute Indian Reservation was the site of deposition of sediments that compose more than 5,500 ft (1,676 m) of sedimentary rocks. Thickness trends and facies distribution were influenced by the interaction of rising uplands and subsiding basins.

The area was part of a stable cratonic shelf during much of pre-Pennsylvanian time, and this is reflected in the resultant carbonate rocks and fine-grained clastic rocks. Deposition in Pennsylvanian and Permian time was dominated by the subsiding Paradox basin and the rising ancestral Uncompahgre and San Luis highlands. In Triassic time deposition occurred on a relatively stable alluvial apron that bordered highlands located to the east of the Reservation. Fine-grained sediments were deposited near sea level during Middle Jurassic time, but active uplift and volcanism on the west coast of the continent during the Late Jurassic caused a renewed flood of coarser clastic sediments into the Reservation area. The present structural setting of the Reservation on the north side of the San Juan Basin did not develop until the time of the Cretaceous to Tertiary Laramide orogeny.

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