Stratigraphy, Structure, and Paleogeography of Pennsylvanian and Permian Rocks, San Juan Basin and Adjacent Areas, Utah, Colorado, Arizona, and New Mexico

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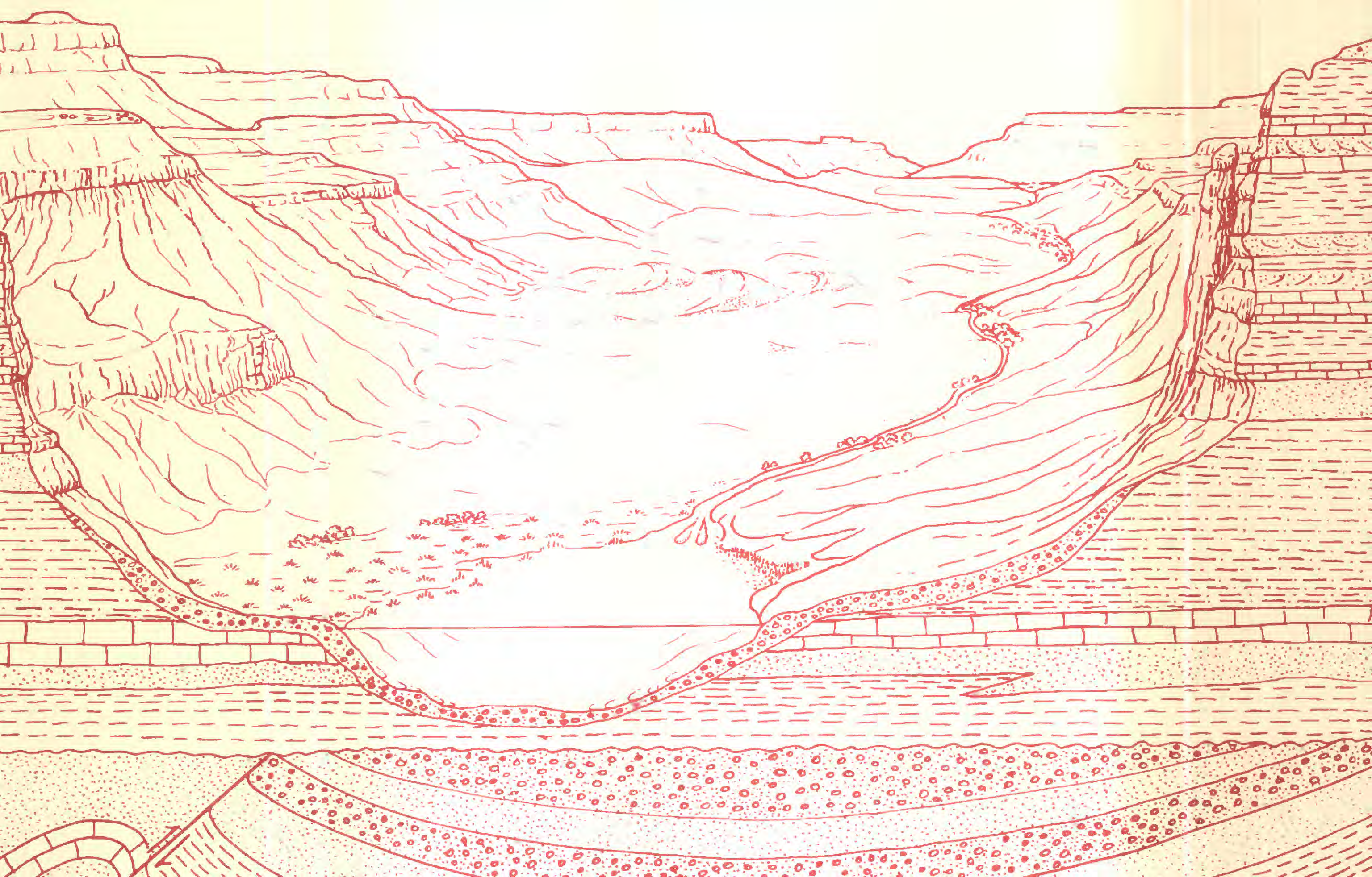

Chapter O

Stratigraphy, Structure, and Paleogeography of Pennsylvanian and Permian Rocks, San Juan Basin and Adjacent Areas, Utah, Colorado, Arizona, and New Mexico

By A. CURTIS HUFFMAN, JR., and STEVEN M. CONDON

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1808

EVOLUTION OF SEDIMENTARY BASINS—SAN JUAN BASIN

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CONTENTS

PLATES

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FIGURES

Stratigraphy, Structure, and Paleogeography of Pennsylvanian and Permian Rocks, San Juan Basin and Adjacent Areas, Utah, Colorado, Arizona, and New Mexico

By A. Curtis Huffman, Jr., *and* Steven M. Condon

Abstract

During the Late Mississippian, the area of the present-day San Juan Basin was located on a carbonate platform at the edge of the craton. Following sea-level drop and (or) tectonic uplift, an unconformity of regional extent developed on this platform, upon which continental sediments of the Mississippian(?) and Pennsylvanian Molas Formation in the north and the Mississippian Log Springs Formation in the southeast were deposited. Subsequently, during the Early Pennsylvanian, downwarping of the San Juan Basin area was accompanied by transgression of the sea and deposition of carbonate rocks of the upper part of the Molas. Together, the Molas and Log Springs Formations are 0–170 ft (0–52 m) thick in the area of the basin.

The Pennsylvanian was a time of accelerated downwarping and simultaneous uplift of northwest-oriented highlands on the northeastern margin of the basin. Positive areas to the west and the southwest defined the opposing margins of the northwest-oriented Paradox Basin and a southeast extension of it, the San Juan trough. The San Juan trough roughly approximates the area of the present-day San Juan Basin.

A mixed assemblage of clastic, carbonate, and evaporite sediments comprising the Hermosa Group, Rico Formation, and Cutler Group was deposited in the Paradox Basin and San Juan trough during the Pennsylvanian and Permian. The Hermosa Group consists of the Pinkerton Trail (0–225 ft, 0–69 m), Paradox (0–2,285 ft, 0–696 m), and Honaker Trail (0–1,390 ft, 0–424 m) Formations. Equivalent rocks in the southeastern part of the San Juan Basin are the Sandia Formation and Madera Limestone.

The Pinkerton Trail and Sandia Formations are composed of marine carbonate rocks, thin interbeds of black shale, and sandstone. The Paradox Formation is composed mainly of cyclically deposited beds of salt, anhydrite, carbonate rocks, and black shale. This assemblage is confined principally to the northwestern corner of the study area, northwest of the Hogback monocline. Correlative rocks outside the area of evaporite deposition are composed of biohermal and shelf carbonate rocks and black shale to the southwest and southeast and arkosic clastic rocks and red and green shale to the northeast. The Honaker Trail Formation records a return to normal marine sedimentation; tabular carbonate rock bodies were deposited in much of the basin, and clastic rocks were deposited on the north side of the basin. The Madera Limestone is only recognized on the southeast side of the San Juan Basin where rocks of the Paradox and equivalent carbonate rocks cannot be recognized.

Infilling of the Paradox Basin and San Juan trough occurred during the Early Permian when the highlands to the northeast experienced renewed uplift, and coarse clastic rocks gradually displaced marine water from the depositional basin. A sequence of interbedded marine carbonate and red clastic rocks of the Rico Formation records the onset of this infilling process. This interbedded sequence can be traced through most of the San Juan Basin and is 0–275 ft (0–84 m) thick in the study area.

Permian rocks in much of the San Juan Basin are assigned to the Cutler Group, which is divided into the Halgaito Formation (0–1,005 ft, 0–306 m), Cedar Mesa Sandstone (0–630 ft, 0–192 m), Organ Rock Formation (0–1,555 ft, 0–474 m), and De Chelly Sandstone (0–915 ft, 0–279 m). In the western part of the basin correlative rocks are assigned to the Supai Formation (450–755 ft, 137–230 m) and in the southern and eastern parts to the Abo (250–675 ft, 76–241 m) and Yeso (15–525 ft, 4.5–160 m) Formations and the Glorieta Sandstone (75–300 ft, 23–91 m). The San Andres Limestone (0–195 ft, 0–59 m), the uppermost Permian unit recognized, is in the south-central part of the basin.

Permian rocks of the San Juan Basin reflect an interplay between abundant sediment supply from highlands to the northeast and cyclic marine incursions from the southwest and south. Rocks of the Halgaito, Organ Rock, Supai, and Abo

Formations were deposited in mixed fluvial and eolian environments. The Cedar Mesa Sandstone was deposited in an evaporite-rich subbasin in the northwestern part of the study area and grades to fluvial strata to the north, east, and south. The De Chelly Sandstone and Meseta Blanca Sandstone Member of the Yeso Formation are principally eolian erg and erg-margin deposits. The Glorieta Sandstone is an erg and marginal-marine deposit. The San Ysidro Member of the Yeso Formation and the San Andres Limestone are marine and marginal-marine deposits. Uplift and erosion produced a regional unconformity between Permian rocks and overlying Triassic rocks.

The cyclicity of Pennsylvanian and Permian sedimentary deposits reflects an interaction between climatic, eustatic, and tectonic controls. Eustatic fluctuations resulted from periods of continental glaciation in southern Gondwana. The tectonic influence was produced by orogenic movements in the Ancestral Rocky Mountains in response to the collision between Laurentia and Gondwana. Large stresses transmitted along continental-scale shear zones from the areas of collision along the southeastern and southern margins of North America produced vertical and lateral movements along preexisting zones of weakness in the Ancestral Rocky Mountains. Movement on northeasterly and northwesterly trending faults strongly influenced deposition on both regional and local scales.

Paleogeographic reconstructions indicate that the area retained a fairly constant position relative to both the Pangean land mass and the Equator during this time. Local topography probably did not vary much from Middle Pennsylvanian through Early Permian time, and the highlands of the Uncompahgre probably were the single most dominant factor. Throughout this interval the Paradox Basin–San Juan trough was an elongate, subsiding depocenter downdip and downwind of the Uncompahgre–San Luis highlands but probably never itself was very high above sea level.

INTRODUCTION

The investigation described herein is a part of the U.S. Geological Survey Evolution of Sedimentary Basins Program. This report concerns the Pennsylvanian and Permian stratigraphic framework, structural development, and paleogeography of the San Juan Basin.

Due to the large amount of subsurface information and the limited paleontologic data available, our study emphasized correlation of lithostratigraphic units. Many, if not most, of the units are time transgressive, and the ages of some units are not well constrained. Although the concept of time is inherent in a consideration of basin evolution, strata were not arbitrarily assigned to or excluded from formations or members because of their age. This approach is a problem only with strata around the Mississippian-Pennsylvanian and Pennsylvanian-Permian boundaries.

Acknowledgments.—Thanks to S.Y. Johnson and J.L. Ridgley for their constructive reviews and criticisms. We also acknowledge the many discussions and field trips with D.L. Baars, D.H. Buckner, J.A. Campbell, R.J. Hite, J.A. Peterson, and J.D. Stanesco, among others, during which many of the ideas expressed here were formulated. Special thanks to M.E. MacLachlan for all her good advice, both heeded and unheeded.

Regional Setting

The San Juan Basin is a large physical and structural feature in northwestern New Mexico and southwestern Colorado (fig. 1), on the southeastern margin of the Colorado Plateau physiographic province. It is bounded on the north by the San Juan Volcanic Field, the Needles, Rico, and La Plata Mountains, and Sleeping Ute Mountain; on the west by the Carrizo, Lukachukai, and Chuska Mountains and the Defiance Plateau; on the south by the Zuni Mountains; and on the east by the Nacimiento and San Pedro Mountains. Topographically low areas extend from the basin to the northwest into southeastern Utah and to the southeast into the Acoma sag and southwest into the Gallup sag on either end of the Zuni Mountains. The terrain of the interior of the basin consists of mesas, canyons, and valleys eroded in almost flat-lying Upper Cretaceous and Tertiary bedrock. There are no deep canyons or local uplifts in the central part of the basin that expose older rocks; the only exposures of Pennsylvanian and Permian rocks are on the bounding uplifts on the basin margins (fig. 1). Because these uplifts also receive the most rainfall in the region, vegetation obscures many outcrops.

The San Juan Basin evolved to its present structural configuration (fig. 2) during the Late Cretaceous to Oligocene Laramide orogeny. Most of the surrounding uplifts, many of the monoclines, and some of the smaller internal structures, although Laramide in present form, show abundant evidence of having been inherited from older structural features (Mallory, 1972). During the late Paleozoic, the area of the present San Juan Basin was part of the San Juan trough, a shallow southeastern extension of the Paradox Basin (fig. 3). This trough has been referred to as the Cabezon sag or Cabezon accessway (Wengerd and Matheny, 1958), part of the Paradox Basin (Szabo and Wengerd, 1975), or the San Juan trough (Peterson and Smith, 1986), depending on the emphasis of the authors. We prefer the name San Juan trough because of its locational and descriptive clarity as well as its parallelism with the name Colorado trough for the area on the other side of the Uncompahgre uplift to the north. Subsidence rates in the San Juan trough were greatest during the Middle Pennsylvanian to Early Permian period of maximum deformation in the Ancestral Rocky Mountains.

During the Pennsylvanian and Permian, the San Juan trough was bounded on the northeast by the Uncompahgre uplift–San Luis highlands, on the southwest by the

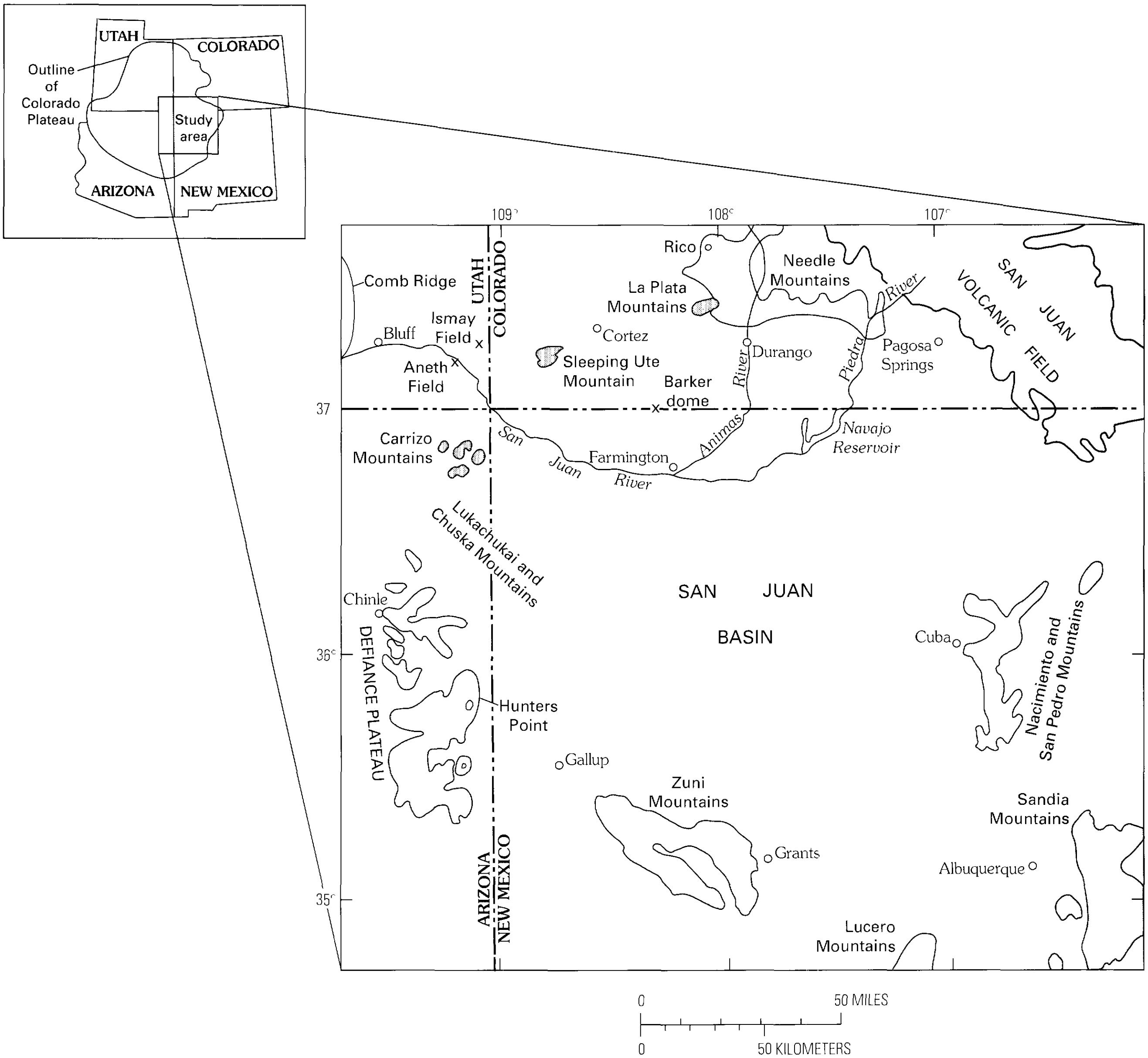


Figure 1. Pennsylvanian and Permian outcrops (light shading) in the San Juan Basin and adjacent areas. Selected oil and gas fields (marked by x's) and areas of intrusive rocks (dark shading) are also shown.

Defiance-Zuni platform, and on the east and southeast by the Pedernal and Peñasco highlands (fig. 3). The trough was separated from the Paradox Basin by a fault underlying the present position of the Hogback monocline. Movement along this fault was intermittently down to the northwest throughout the Pennsylvanian and Permian. Apparent movement on the faults along the Uncompahgre–San Luis front was strongly down to the southwest; the resulting asymmetric basin had its axis near its northeastern margin. Farther to the northwest in the Paradox Basin, this movement has been shown to be thrust faulting (Frahme and Vaughn, 1983), and significant lateral movement on many of these faults may also have occurred (Baars and Stevenson, 1981). The sense and magnitude of movement have not yet been conclusively demonstrated.

A complex set of stratigraphic names characterizes the Pennsylvanian and Permian Systems in the area of the San Juan Basin (fig. 4). This nomenclature developed because Paleozoic outcrops in widely separated areas were studied and named at different times by different people and because subsurface control between outcrops was widely spaced or nonexistent at the time of the early studies. Subsurface control has improved over the years due to oil and

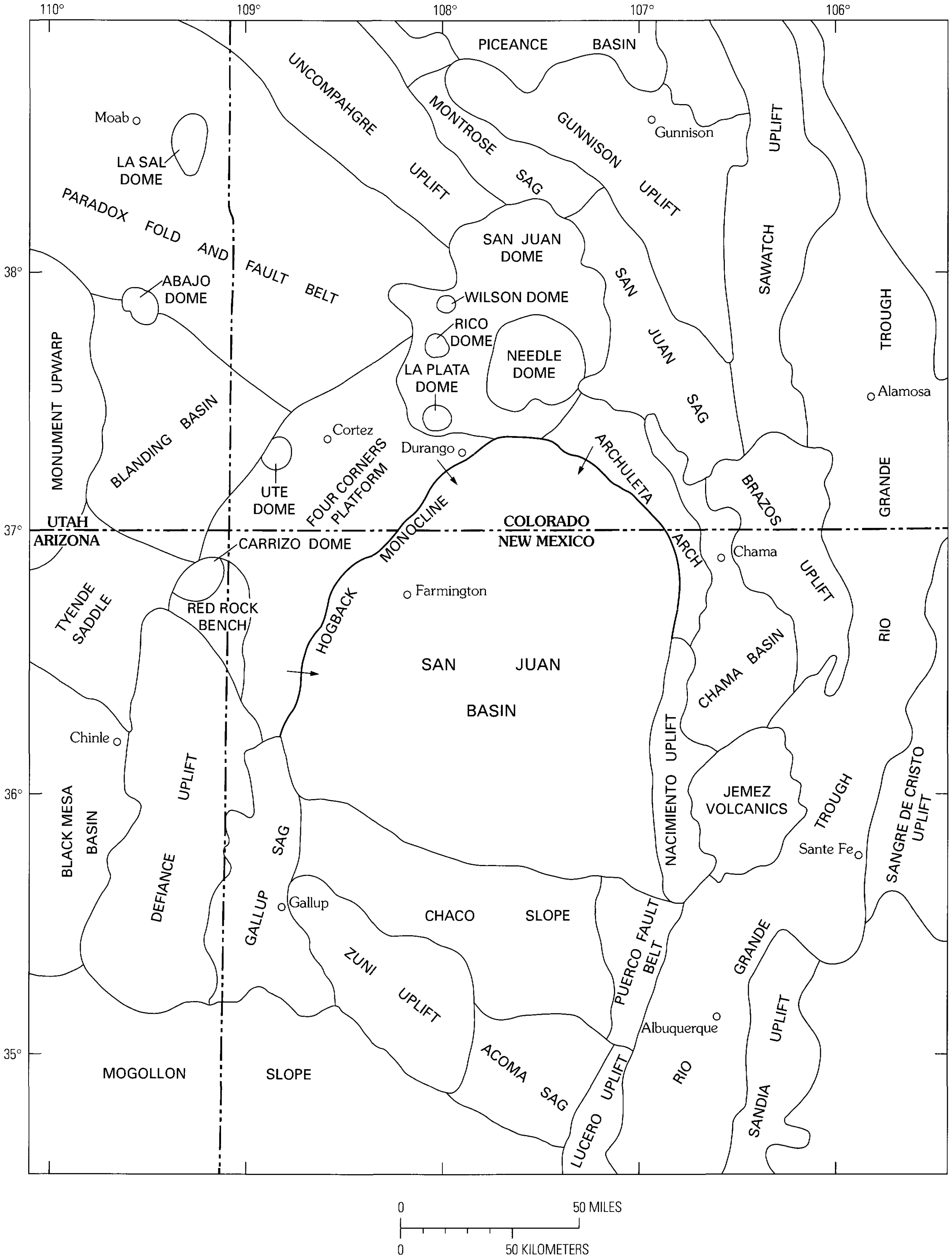


Figure 2. Laramide structural elements in the San Juan Basin and adjacent areas. Modified from Kelley and Clinton (1960), Grose (1972), and Woodward (1974).

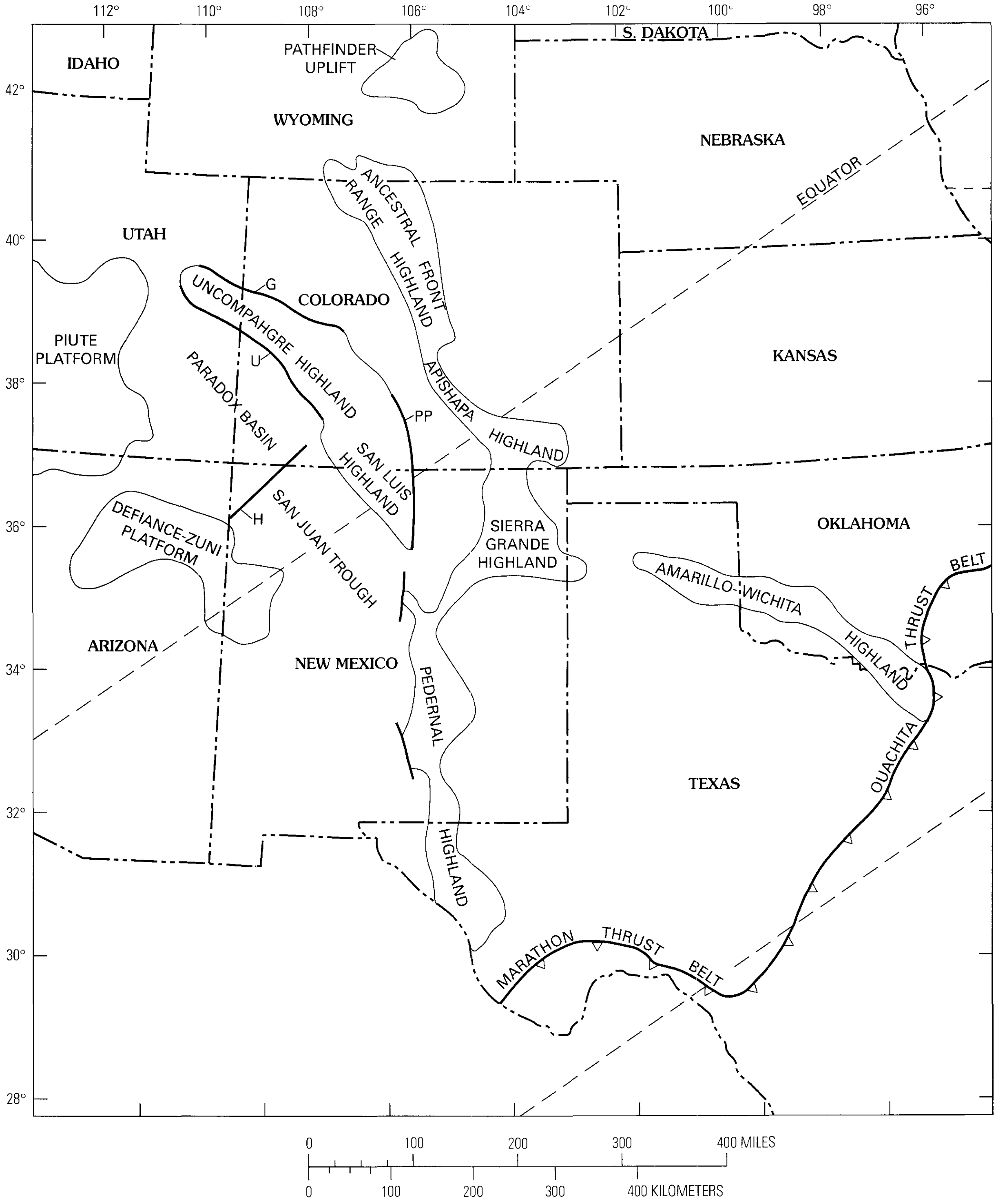
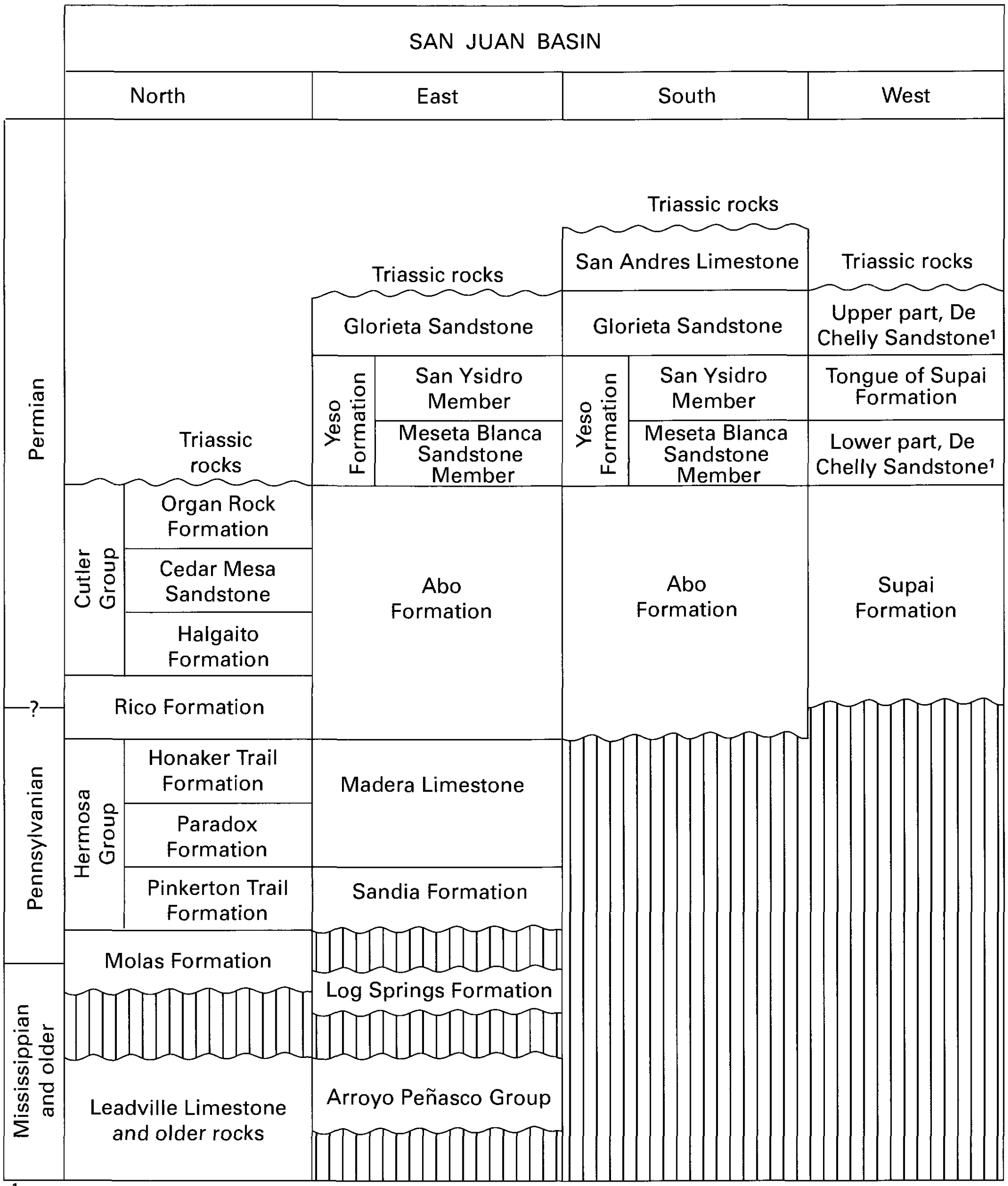


Figure 3. Paleogeography of the Ancestral Rocky Mountains region during Middle to Late Pennsylvanian time. Location of paleoequator for the Late Pennsylvanian is from Scotese and McKerrow (1990). Pennsylvanian faults: H, Hogback fault; U, Uncompahgre fault; G, Garmesa fault; PP, Picuris-Pecos fault. Modified from Lindsey and others (1986).

gas exploration; however, there are still extensive areas where no data are available. Other factors that contributed to the development of the varied nomenclature are complex facies changes in Pennsylvanian and Permian rocks from one side of the basin to the other and sparse fossil control, especially in the Permian. Figures 5 and 6 are cross sections that show regional relations of Pennsylvanian and Permian rocks in the basin.



[1]Of Cutler Group

Figure 4. Stratigraphy of the San Juan Basin during late Paleozoic time. Location of Pennsylvanian-Permian boundary is uncertain.

Previous Investigations

The following discussion, although not comprehensive, includes many of the stratigraphic studies conducted in the San Juan Basin and vicinity. Regional studies of Pennsylvanian rocks were conducted by Read and Wood (1947), Wengerd and Strickland (1954), Wengerd and Matheny (1958), Wengerd (1962), Mallory (1972), and McKee and Crosby (1975). Similar studies of Permian rocks were conducted by Baker and Reeside (1929), Baars (1962), McKee and others (1967), and Rascoe and Baars (1972).

The earliest studies of Pennsylvanian and Permian rocks in the northern San Juan Basin were conducted by Cross and Purington (1899), Cross and Spencer (1900), and Cross and others (1905), who mapped, measured, described, and correlated rocks in the area surrounding the Needle and Rico Mountains. Eckel (1949, 1968), Read and others (1949), Wengerd (1957), Fetzner (1960), Hite (1960), Girdley (1968), Pratt (1968), Jentgen (1977), Campbell (1979, 1980, 1981), and Baars and Ellingson (1984) also described Paleozoic rocks in the northern part of the basin. Paleozoic rocks on the western side of the basin on the Defiance Plateau and on the southern side of the basin in the Zuni Mountains were studied by Read (1951), Allen and Balk (1954), Read and Wanek (1961), Peirce (1967), and Baars and Stevenson (1977). Paleozoic

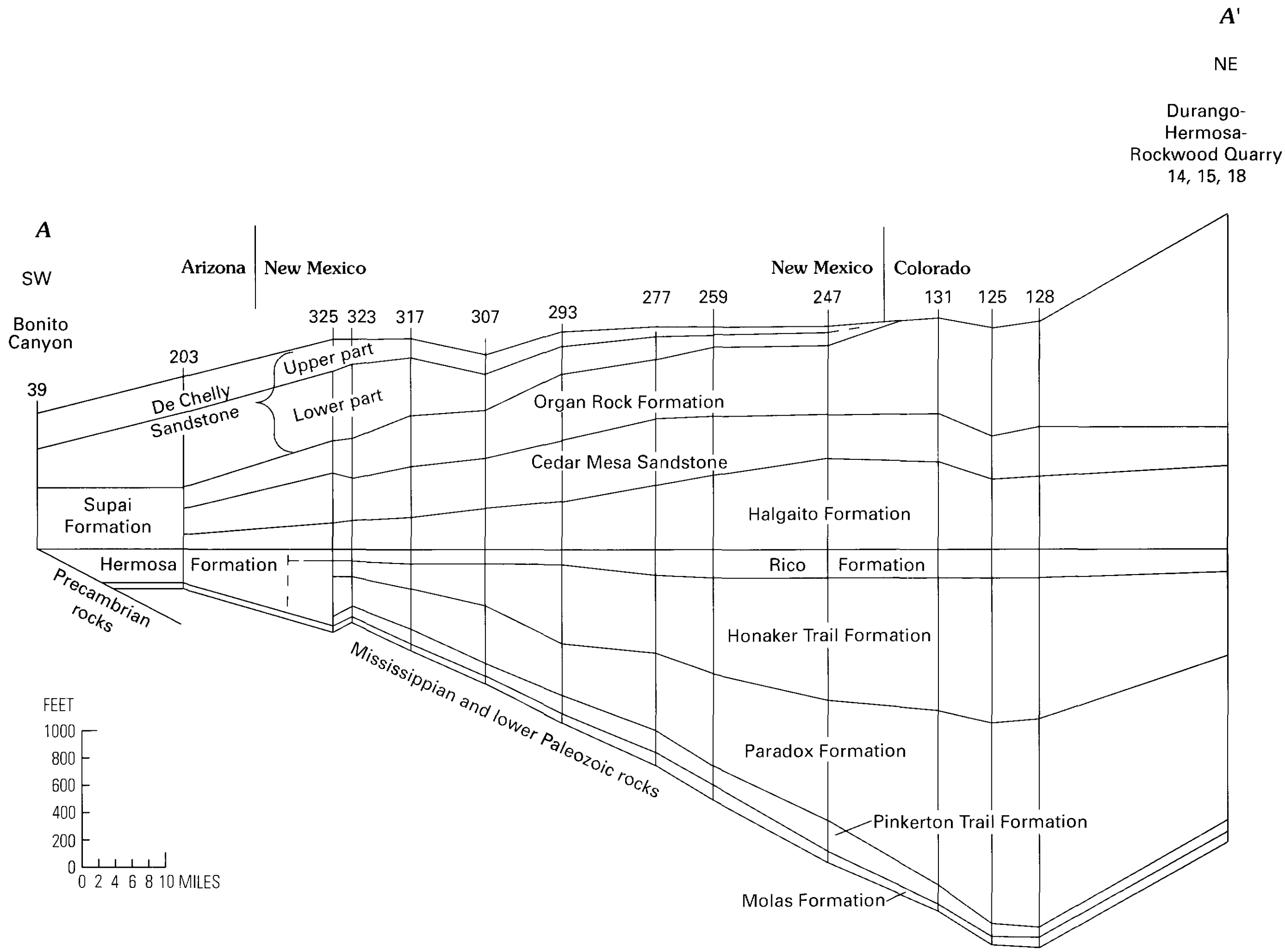


Figure 5. Cross section *A–A'* showing southwest-northeast correlations of Pennsylvanian and Permian rocks in the San Juan Basin and adjacent areas. Numbers along tops of sections refer to well and measured section numbers in appendix tables A1 and A2. Line of section shown on plate 1.

rocks on the eastern side of the basin were described by Henbest and others (1944), Wood and Northrop (1946), Read (1951), Smith and others (1961), Muehlberger (1967), Bingler (1968), Baars (1974), DuChene (1974), DuChene and others (1977), and Woodward (1987). The sedimentary history of the basin was summarized by Peterson and others (1965).

Methods

This study began with a reconnaissance examination of Pennsylvanian and Permian outcrops on the bounding uplifts and in areas adjacent to the San Juan Basin. These observations were followed by inspection of approximately 350 geophysical logs of wells that penetrate into or through Permian and older rocks within and adjacent to the basin. Log types consist of dual induction Laterologs (focused-current logs) or induction-electrical logs with spontaneous-potential, resistivity, and conductivity curves, radioactivity logs with gamma-ray and neutron curves, interval transit time logs (sonic logs), and density logs. Generally, several log types are available for each hole. The initial list of available logs was retrieved from the Well History Control System (WHCS) file of Petroleum Information, Inc. A few other logs were located that are not in the WHCS file. All of the logs used are from wells drilled before 1986, but not all of the available holes were used. In some developed fields the density of drill holes is greater than that needed for this study. See appendix table A1 for a list of the drill holes used and plate 1 for their locations. (Plate 1 also shows locations of additional wells and outcrops used in a companion study of younger stratigraphic units.)

One problem encountered in gathering subsurface information was acquiring an even distribution of data across the basin. Much of the drilling to older formations is on the structurally shallow Four Corners platform and

Defiance uplift on the western side of the Hogback monocline (pl. 1, fig. 2). Several deep holes are located on the southeastern side of the basin, but only widely scattered borehole control points are available in the central part of the basin.

Preliminary tops of stratigraphic units were located, or "picked," for each unit of Jurassic age or older. Previous subsurface studies by Wengerd and Matheny (1958), Baars (1962), Irwin (1977), and Molenaar (1977) were used as guides for our preliminary picks. Seven cross sections, four trending northeast-southwest and three trending northwest-southeast, were constructed that cross the basin at regular intervals (see Huffman and Condon, in press, and Condon and Huffman, in press). Picks of formation and member tops were revised on these cross sections, and then the other logs were correlated into the cross sections. Figures 5 and 6 are schematic representations of two of these cross sections.

In addition to the well-log data, data from 22 measured outcrop sections (appendix table A2, pl. 1) were used to calculate the isopach maps (pls. 2–16). Most of these sections are from published studies.

Geologic maps were a third source of data. Where possible, elevations of selected geologic contacts were recorded at a density of about one per township. These data were used to tie structure contour maps to surface outcrops.

Thickness files of the various stratigraphic units were then compiled, and the thickness data were gridded and contoured using the Interactive Surface Modelling (ISM) software of Dynamic Graphics, Inc. The data were gridded with 4-mi (6 km) spacing for the isopach maps (pls. 2–16) and 1.3-mi (2 km) spacing for the structure contour maps (pls. 17, 18). Four data points were used to calculate each grid node. The number of control points used to construct the maps differs for various stratigraphic units, depending on how many wells penetrated that unit. In general, the number of data points is about the same for the Permian and Pennsylvanian units down to the stratigraphic position of the Honaker Trail Formation of the Hermosa Group. Because the upper part of the Paradox Formation of the Hermosa Group was the drilling objective for many of the deep wells, that unit and underlying units have fewer control points with which to construct isopach maps. The locations of well logs and measured sections used to calculate a particular map are shown on the map.

After preliminary isopach and structure contour maps were plotted, problem areas that seemed too thin, too thick, or at an abnormally high or low structural elevation were rechecked. The maps were regridded and contoured; small areas were smoothed by hand. Because the contour maps are computer generated, there is less precision at the edges of the maps where the data end than in the central parts of the maps where control is better.

STRATIGRAPHY

Summary of Depositional History

Prior to deposition of Pennsylvanian strata, the area of the San Juan Basin was a subaerial plain of low relief that had developed on mixed carbonate and clastic pre-Pennsylvanian rocks. A regolith that developed on this surface in Late Mississippian time is preserved as the basal part of the Log Springs Formation (southeastern part of basin) and is likely present in the basal part of the Molas Formation (northern part of basin). The upper part of the Molas was deposited during the Early Pennsylvanian when regional downwarping allowed marine waters to flood the area.

Downwarping continued throughout the Pennsylvanian and was accompanied by uplift of the Uncompahgre and San Luis highlands to the north. The Defiance-Zuni area on the southwestern side of the basin remained a positive feature but was not an important source of sediment. The Peñasco uplift, a precursor to the Nacimiento Mountains, was a minor positive area on the eastern side of the basin. The far west margin of the depositional basin, in east-central Utah, was bounded by the Piute platform.

During the Pennsylvanian, the depositional basin bounded by these uplifts consisted of the Paradox Basin in the northwest and the San Juan trough to the southeast. A low submarine barrier, in the approximate position of the Hogback monocline (fig. 2), separated the two subbasins. Marine water entered the basin-trough from the northwest and west through the Oquirrh and Fremont sags and from the southeast through the Cabezon sag (Wengerd, 1962, p. 271). The depositional basin was markedly asymmetrical; a deep trough on the northeastern side extended southeastward through the San Juan Basin area and is reflected in isopachs for the total Pennsylvanian System and the Halgaito Formation.

As the depositional basin developed during Middle Pennsylvanian time, sediments were deposited in a wide variety of environments including fluvial, shallow marine, open marine, and evaporite basin. Carbonate and evaporite rocks were deposited in the central part of the depositional basin and mixed carbonate and clastic rocks along the northern, eastern, and southwestern margins. The initial deposits above the Molas are the Pinkerton Trail Formation in most of the San Juan Basin and the Sandia Formation in the southeastern part of the basin.

Accelerated downwarping accompanied by cyclic eustatic sea-level changes led to accumulation of thick salt and other evaporite beds in the Paradox Basin and northwestern San Juan trough. This sequence of evaporites is known as the Paradox Formation. On the northeastern side of the depositional basin the evaporites grade

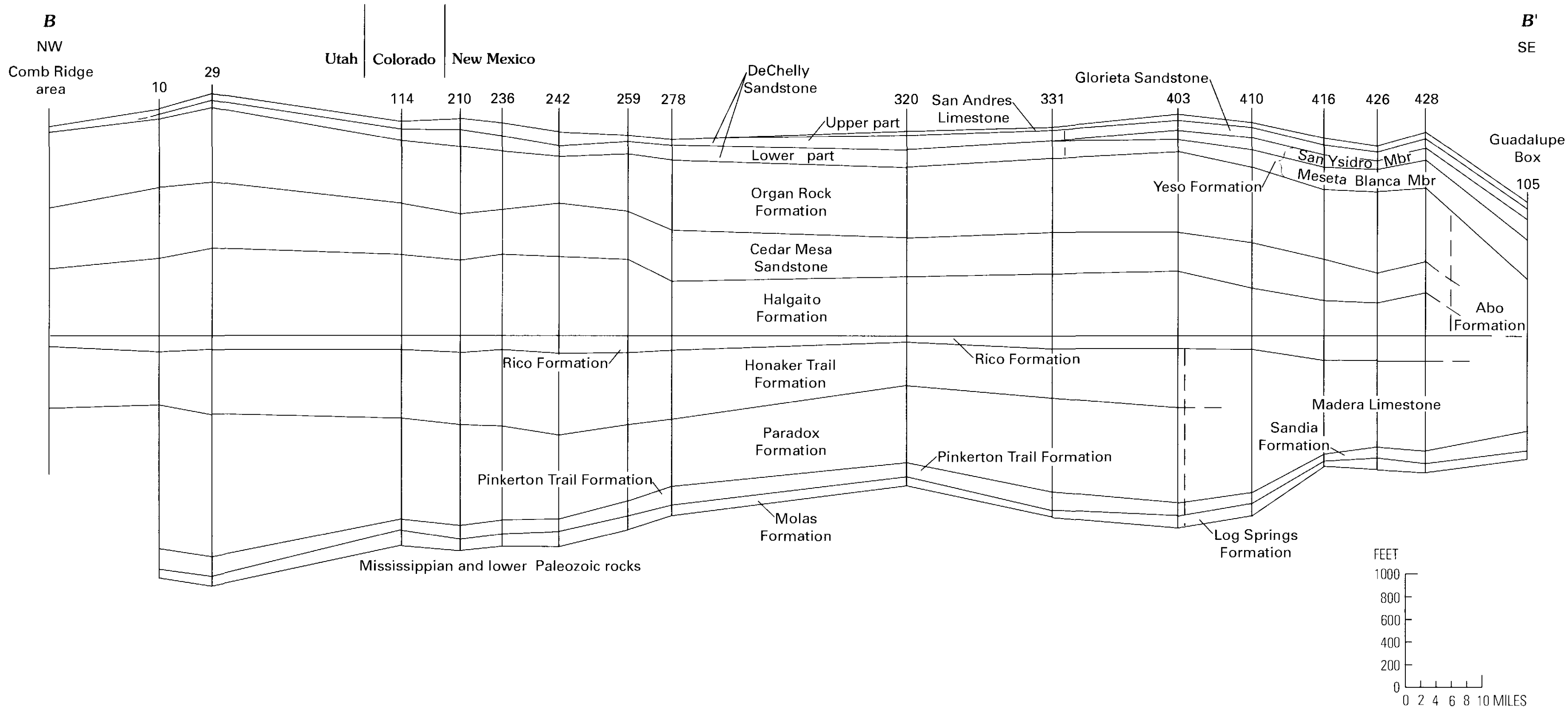


Figure 6. Cross section *B–B′* showing northwest-southeast correlations of Pennsylvanian and Permian rocks in the San Juan Basin and adjacent areas. Numbers along tops of sections refer to well and measured section numbers in appendix tables A1 and A2. Line of section shown on plate 1.

abruptly into coarse arkosic clastic rocks, and on the southwestern side they grade to shelf carbonate rocks and associated biohermal buildups. Distinctive black shale beds can be traced from the evaporite sequence of the Paradox Formation into the equivalent carbonate and clastic units.

Carbonate rocks of the Honaker Trail Formation record a return to normal marine conditions after deposition of the Paradox Formation. The Honaker Trail grades northward into clastic rocks that were shed from the Uncompahgre upland. In the southeastern part of the San Juan trough open-marine sedimentation prevailed during deposition of the Paradox and Honaker Trail Formations, producing the Madera Limestone. In much of the San Juan Basin the Pennsylvanian-Permian boundary is marked by intertonguing carbonate and clastic beds of the Rico Formation that document the change from dominantly marine to dominantly continental deposition.

During the Permian, sedimentation in the San Juan trough followed the pattern established in the Pennsylvanian. The Uncompahgre highland continued to rise and shed a great volume of arkosic debris. Near the mountain front, debris flows deposited large boulders of Precambrian granite in the Cutler Formation. The load of clastic debris contributed to development of salt anticlines, which formed when salt of the underlying Paradox Formation flowed upward into diapiric structures. South and west of the Paradox fold and fault belt (fig. 2), wind and water winnowed the sediments being shed from the Uncompahgre into several formations of the Cutler Group. The Halgaito and Organ Rock Formations were deposited in relatively low energy environments near sea level, and the intervening Cedar Mesa Sandstone was deposited in eolian, shallow-marine, and sabkha environments. Simultaneous deposition on the southwestern side of the San Juan trough is recorded by the Supai Formation and on the southern and eastern sides by the Abo Formation.

A general drying of the San Juan Basin area in the Permian produced deserts in which the lower part of the De Chelly Sandstone and the Meseta Blanca Sandstone Member of the Yeso Formation were deposited. The Meseta Blanca is recognized in the southeastern part of the basin and the De Chelly elsewhere. Incursion of a sea from the south produced a northward-thinning wedge of shallow-marine and sabkha deposits of the San Ysidro Member of the Yeso Formation.

In much of the San Juan Basin the upper part of the De Chelly Sandstone directly overlies the lower part of the De Chelly; in the southeastern part of the basin, however, the correlative Glorieta Sandstone overlies the San Ysidro Member (fig. 6). A final transgression of the sea is recorded by the San Andres Limestone. Any subsequent Permian deposition in the area was removed by pre-Moenkopi or pre-Chinle erosion.

Mississippian and Pennsylvanian Rocks

The Molas Formation was named by Cross and others (1905, p. 4) for exposures near Molas Lake, north of Durango, Colo. The Molas was later divided into three members: the Coalbank Hill Member at the base, the middle member, and the upper member (Merrill and Winar, 1958, 1961). Although the individual members have not been recognized outside the San Juan Mountains north of the San Juan Basin, their descriptions are characteristic of the Molas over most of its extent in southwestern Colorado, southeastern Utah, northeastern Arizona, and northwestern New Mexico (pl. 3). We made no attempt to identify the members in the San Juan Basin.

The Coalbank Hill Member of the Molas Formation consists of red, purplish-red, and reddish-brown siltstone and 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 (regolith) deposit that developed on top of the Mississippian Leadville Limestone. In some areas, such as at Coalbank Hill itself, the Leadville is absent and the regolith of the Molas rests unconformably on the Devonian Ouray Limestone (Merrill and Winar, 1958, p. 2117). No age-diagnostic fossils that could be used to precisely date the Coalbank Hill Member have been found. Merrill and Winar considered the Mississippian-Pennsylvanian boundary to lie within the Coalbank Hill Member or the overlying middle member.

The middle member is a heterogeneous unit that consists of interbedded reddish-brown shale, siltstone, mudstone, sandstone, and conglomerate. The conglomerate consists mainly of chert pebbles, but limestone pebbles are present locally (Merrill and Winar, 1961, p. 85). The average thickness of the middle member is 40 ft (12 m). Sediments of this member were deposited by streams that reworked the underlying paleosol or older rock units. Merrill and Winar (1958, p. 2117) interpreted the contact between the middle member and the Coalbank Hill Member as an unconformity.

The upper member of the Molas consists of the same diverse rock types that compose the middle member and also some beds of fossiliferous limestone. In contrast to the reddish-brown color of the lower two members, the upper member contains sandstone beds that are maroon, pink, and light gray. Sandstone units of the upper member are more laterally continuous than those of the middle member (Merrill and Winar, 1958). Limestone of the upper member contains Pennsylvanian marine fossils including brachiopods, bryozoans, echinoderms, and foraminiferans (Merrill and Winar, 1958, p. 2123). The average thickness of the upper member is about 25 ft (8 m). Sediments of the upper member were deposited partly by streams that reworked preexisting Molas sediments and older rocks and partly by the transgressing Pennsylvanian sea.

The only way Merrill and Winar (1958, p. 2119) were able to distinguish the middle member of the Molas from the upper member was by laboratory analysis of the clay composition of the units. They defined the top of the middle member 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 between the middle and upper members could only be approximated. The middle and upper members cannot be distinguished using the subsurface control available in the San Juan Basin.

The Log Springs Formation, named by Armstrong (1955) for exposures in Peñasco Canyon in the southern Nacimiento Mountains (fig. 1), is lithologically similar to the Coalbank Hill Member and the middle member of the Molas Formation. The Log Springs unconformably overlies the Mississippian Arroyo Peñasco Group. Basal strata of the Log Springs developed as regolith on the underlying carbonate rocks. The upper part of the Log Springs consists of shale, sandstone, and conglomerate (Armstrong and Holcomb, 1989, p. D6).

The Log Springs is inferred to be Late Mississippian in age because of its stratigraphic position in relation to units that have been dated using microfauna (Armstrong and Holcomb, 1989, p. D6). The basal Coalbank Hill Member of the Molas is thought by some to be all or partly Mississippian (Armstrong and Holcomb, 1989, p. D6).

The Log Springs Formation and Molas Formation are interpreted as the same lithostratigraphic unit in this report and are mapped together on plate 2, but, because it was not possible to identify just the Pennsylvanian part of the Molas on the well logs, the map of all Pennsylvanian rocks (pl. 3) does not include the Molas. Because the Molas is so thin, a map that includes the Molas with overlying Pennsylvanian rocks (A.C. Huffman, Jr., and S.M. Condon, unpublished data) does not differ substantively from one that does not (pl. 3).

The Molas and Log Springs Formations are 0–170 ft (0–52 m) thick in the study area. A band of thick Molas oriented northwest-southeast crosses the Four Corners area and extends into the Cuba, N. Mex., area (pl. 2). It then extends southeastward from Cuba to outcrops of the Log Springs in the Nacimiento Mountains. Another thick area of Molas is in the Piedra River Canyon, northwest of Pagosa Springs, Colo.

The zero line that delimits the edge of the Molas and Log Springs on the southern and eastern sides of the basin is a result of both nondeposition and postdepositional erosion. In the Zuni Mountains on the southern side of the basin there is only a thin sequence of possibly Pennsylvanian rocks; Armstrong and Holcomb (1989, p. D10) indicated that this area was positive in the Late Devonian and Mississippian. It is likely that this area remained slightly positive during the Pennsylvanian, although it was not a significant source of Pennsylvanian clastic sediments. Woodward (1987, p. 48) stated that the Nacimiento Mountains area on the east was a stable positive area through the Devonian and experienced episodic uplift during the Mississippian, Pennsylvanian, and Permian. The Log Springs is only locally preserved in the Nacimiento Mountains (Woodward, 1987, p. 21).

Pennsylvanian Rocks

Hermosa Group and Equivalent Rocks

Pennsylvanian formations in the northern part of the San Juan Basin are part of the Hermosa Group, originally described as a formation by Cross and Spencer (1900) for exposures north of Durango, Colo. Wengerd and Matheny (1958) raised the unit to group status where it can be divided into mappable units. The Hermosa consists of, from oldest to youngest, the Pinkerton Trail (0–225 ft, 0–69 m), Paradox (0–2,285 ft, 0–696 m), and Honaker Trail (0–1,390 ft, 0–424 m) Formations. The nomenclature of Wengerd and Matheny is used in this report. Equivalent rocks in the southeastern part of the basin are the Sandia Formation (0–185 ft, 0–56 m) and Madera Limestone (0–1,290 ft, 0–393 m). In the Piedra River Canyon, northwest of Pagosa Springs, Colo., and in part of the Defiance Plateau on the western side of the basin, the three formations of the Hermosa Group cannot be distinguished separately. In those areas the unit is recognized as the undivided Hermosa Formation. Pennsylvanian rocks of the San Juan Basin and vicinity (excluding the Molas and Rico Formations) are 0–3,455 ft (0–1,054 m) thick (pl. 3). South of the pinchout of Mississippian rocks, basal Pennsylvanian strata unconformably overlie Precambrian rocks.

The configuration of the Pennsylvanian depositional basin is evident on plate 3. The thickest sequence of Pennsylvanian rocks was deposited in the central Paradox Basin, which on plate 3 includes Utah and that part of Colorado northwest of Durango. The axis of the San Juan trough swings southeastward toward Albuquerque, N. Mex.

Pennsylvanian rocks are also relatively thick in the Gallup sag in the southwestern part of the study area. A 400-ft (122 m) contour bracketed by zero lines in the area of the Zuni Mountains and the Defiance plateau indicates that the sag either accumulated more sediment during the Pennsylvanian or remained protected from post-Pennsylvanian erosion, or both. It is unknown if Pennsylvanian rocks once continued southwestward through a break between the Zuni and Defiance uplands and were continuous with rocks of the Holbrook Basin in Arizona or if there was only a slight reentrant in the combined Zuni-Defiance positive area in which Pennsylvanian sediments accumulated.

The Hermosa Group of the Paradox Basin and San Juan trough consists of four distinct interbedded genetic facies: arkosic, shelf clastic, shelf carbonate, and evaporite (Peterson and Hite, 1969, p. 892). The arkosic facies consists of poorly sorted, conglomeratic arkose and micaceous siltstone in beds that are commonly lenticular and cross-bedded. Southwest transport directions for arkose beds in the Animas River Valley north of Durango (Girdley, 1968, p. 155) indicate that detritus was shed from the ancestral Uncompahgre and San Luis uplands to the northeast (Fetzner, 1960, p. 1396; Peterson and Hite, 1969, p. 892). Arkosic strata are thickest to the north of the study area (Wengerd and Strickland, 1954, p. 2185).

Read and others (1949) diagrammatically showed the extent of the arkosic facies in the Piedra River canyon on the northern side of the basin. They indicated that the arkosic rocks thin and pinch out southward in the canyon into interbedded carbonate rocks. They interpreted the increase in abundance of oxidized red shale and siltstone northward in the arkosic facies as indicating deposition in a more landward direction to the north. The Zuni-Defiance positive area on the southern side of the basin probably was not high enough to have contributed coarse clastic rocks to the Hermosa depositional system.

The shelf-clastic facies consists mainly of fine-grained, well-sorted sandstone on the gently sloping southwestern side of the Paradox Basin. The clastic sediments were most likely shed from the ancestral Kaibab and Zuni-Defiance uplands south and southwest of the Paradox Basin (Fetzner, 1960, p. 1376; Peterson and Hite, 1969, p. 892). Hite and Buckner (1981, p. 156) suggested that these sediments formed mainly by reworking of shoreline deposits 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, contributing to the formation of the basinwide black shale.

The shelf-carbonate facies consists of cyclic deposits of dolomite, limestone, and black, carbonaceous shale on the southeastern, southern, and southwestern shelves of the central Paradox Basin. This lithofacies mainly comprises the rocks of the San Juan Basin east and south of the Hogback Monocline equivalent to the Paradox Formation. In addition to the laterally extensive, tabular shelf-carbonate rocks of this facies, lenticular mound-shaped accumulations of carbonate rock also are present in the upper part of the Paradox. These carbonate mounds are buildups of the leaflike alga *Ivanovia*, which thrived in the shallow-shelf environment (Choquette, 1983). The black shale of this facies grades northeastward into greenish-black siltstone on the margin of the depositional basin (Wengerd and Strickland, 1954, p. 2173).

Periodic subaerial exposure of the carbonate facies resulted in development of disconformities in the carbonate sequence (Wengerd, 1962, p. 311). Secondary porosity of the carbonate mounds, commonly 10 percent or greater (Fassett, 1978), makes this facies important as an oil and gas reservoir. 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 Paradox Formation is present on the northwestern side of the study area and consists of as much as 2,285 ft (696 m) of cyclic deposits of halite and minor black shale, dolomite, limestone, and anhydrite. Halite makes up 70–80 percent of the section in some parts of the Paradox Basin (Peterson and Hite, 1969, p. 893). This facies contains as many as 33 separate beds of halite divided by interbeds of limestone, dolomite, anhydrite, and black shale (Hite, 1960, p. 87; Hite and Buckner, 1981, p. 150). Black shale beds are from a few inches to more than 100 ft (30 m) thick (Wengerd, 1962, p. 312). Complex interbedding of the nonporous elements of the evaporite facies and the porous carbonate mounds of the shelf-carbonate facies has created ideal conditions for stratigraphic trapping of hydrocarbons. The black organic-rich shale beds that serve as the source of the hydrocarbons formed under euxinic conditions. These shale beds, which extend throughout the Paradox Basin from its central part to its shelves, are used widely for subsurface correlation.

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. As a narrowly defined lithostratigraphic unit based on the presence of evaporite, the Paradox extends only about as far southeast as the Hogback Monocline (fig. 2). We recognized rocks equivalent to the Paradox outside the evaporite facies and were able to divide the group into three formations throughout most of the San Juan Basin.

Pinkerton Trail and Sandia Formations

The Pinkerton Trail Formation was named by Wengerd and Strickland (1954, p. 2168) for exposures along Pinkerton Trail, north of Durango, Colo. It 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. Amounts of coarse, clastic detritus in the Pinkerton Trail increase northward from Durango (Fetzner, 1960, p. 1396, 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 the type locality and thickens southward and westward into the Paradox Basin (Wengerd and Strickland, 1954, p. 2169; Wengerd and Matheny, 1958, p.

2065). It attains a maximum thickness of 225 ft (69 m) in the Utah part of the study area and thins to zero on the Defiance Plateau and in the Zuni Mountains (pl. 4). Excellent exposures of the Pinkerton Trail can be viewed along Colorado State 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 when Early Pennsylvanian seas transgressed from the west and southeast (Wengerd, 1957, p. 135; Wengerd and Matheny, 1958, p. 2085). The formation has been interpreted as a shallow shelf deposit by Wengerd (1962, p. 280).

Basal Pennsylvanian rocks in the Nacimiento Mountains were assigned to the Sandia Formation by Wood and Northrop (1946). The Sandia was named for exposures in the Sandia Mountains (Herrick, 1900). DuChene (1974) and DuChene and others (1977) divided the upper clastic member of the Sandia of Wood and Northrop (1946) into the Osha Canyon Formation of Morrowan age at the base and restricted the name Sandia Formation to the upper part of the unit of Atokan age. The Osha Canyon was only recognized in a small area in the southern Nacimiento Mountains (DuChene and others, 1977, p. 1513). Due to its limited outcrop extent and its unknown extent in the subsurface, we included it with the Sandia Formation. The original definition of the Sandia is thus retained, although some or all of the Osha Canyon or lower Sandia may be time equivalent to part of the Molas Formation; the geophysical log response of the Osha Canyon or lower Sandia is very similar to that of the Pinkerton Trail Formation; and the units are mapped together on plate 4.

The lower part of the Sandia consists of light-gray to white, fossiliferous limestone and calcareous shale, and light-gray to tan shale that contains limestone nodules (DuChene and others, 1977, p. 1514). Brachiopods and corals are the most abundant fauna in the unit. The upper part of the Sandia is composed of light-brown, coarse-grained quartz sandstone, green, gray, and yellow shale, siltstone, and silty sandstone, and gray limestone (Woodward, 1987, p. 23).

Together, the Pinkerton Trail and Sandia display thickness trends similar to the Molas and Log Springs (pl. 2) and to the total Pennsylvanian (pl. 3). The units are thickest in the San Juan trough in Utah, Colorado, and northernmost New Mexico and thin on the flanks of the bounding uplifts.

Paradox Formation and Related Rocks

The Paradox Formation, named by Baker and others (1933, p. 13) for exposures in Paradox Valley, Colo., overlies the Pinkerton Trail Formation and is perhaps the most complex sedimentary rock unit in the San Juan Basin. Wengerd (1962, p. 288) noted that the Paradox conformably overlies the Pinkerton Trail in the deeper parts of the Paradox Basin but that a drop in sea level caused the development of disconformities along the northern flank of the basin and on the southwestern shelf.

The Paradox has been divided into cyclic substages (or zones) (Baars and others, 1967), which are, in ascending order, the Alkali Gulch, Barker Creek, Akah, Desert Creek, and Ismay. These zones are bounded by black shale beds and are lithologically diverse, grading from mainly salt, anhydrite, and shale in the central part of the Paradox Basin to shelf-carbonate rocks, sandstone, and shale 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 zones.

Hite and Buckner (1981, p. 150) numbered the evaporite cycles from 1 to 29 (top to bottom), recently increased to 33 (D.H. Buckner, oral commun., 1989), 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 the evaporite facies in the Alkali Gulch, Desert Creek, and Ismay is much less than that in the Akah and Barker Creek. Plate 5 shows the thickness of the Paradox Formation and equivalent rocks and indicates the limits of salt, anhydrite, and black shale in the study area.

Limiting recognition of the Paradox Formation to only the areas where salt or anhydrite is present limits the southern and eastern extent of the Paradox to the northwestern corner of the study area, northwest of the Hogback monocline. Rocks of the shelf facies that are time equivalents to the evaporite facies can be recognized, however, in the eastern and southern parts of the basin by correlation of shale marker beds and carbonate beds (Hite and Buckner, 1981). In addition to these chronostratigraphic correlations, we have been able to separate and trace distinctive lithostratigraphic units of the Hermosa throughout most of the San Juan Basin based on well-log characteristics (Condon and Huffman, in press; Huffman and Condon, in press). The Paradox Formation and related rocks are predominantly thick chemical precipitates (carbonate, anhydrite, halite, or potash) with relatively minor interbedded clastic rocks. Both the Pinkerton Trail and Honaker Trail Formations are composed of thinner chemical rocks interbedded with almost equal amounts of clastic units. Recognition of these characteristics allowed us to map the geometry of the lithologic types and thus general depositional environments even with the types and quality of well logs available.

A precedent was set for more general recognition of the Paradox by Wengerd and Matheny (1958), who included nonevaporite rocks in the Paradox Formation. We 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. By mapping lithostratigraphic rather than chronostratigraphic units we were able to demonstrate the continuity of depositional systems and to extend Paradox Basin nomenclature into the San Juan Basin. Where we were no longer able to identify the three distinct units, we labeled the interval Hermosa Formation undivided or, as in the southeastern part of the basin, we dropped the name entirely and used that criteria to distinguish between the Hermosa Group and the Madera and Sandia Formations.

Honaker Trail Formation

The Honaker Trail Formation was named by Wengerd and Matheny (1958, p. 2075) for exposures at Honaker Trail, along the San Juan River in southeastern Utah. The Honaker Trail 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 is higher both at the base of the unit and toward the center of the basin; the formation includes more clastic rocks both along the northern margin of the basin and in the upper part of the unit (Wengerd, 1957, p. 136). The clastic ratio map of Fetzner (1960, p. 1387) shows a marked increase in clastic rocks in the Honaker Trail Formation along the Uncompahgre front compared to the Paradox and Pinkerton Trail Formations. The Honaker Trail is as thick as 1,390 ft (424 m) in the study area (pl. 6). It shows the same thickness trends as other Pennsylvanian rocks in the basin, the thickest area being in the Paradox Basin and San Juan trough.

The depositional setting of the Honaker Trail was an open-marine basin, similar to that of the Pinkerton Trail Formation and 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 northern side of the Paradox Basin was apparently increasingly active during deposition of the Honaker Trail, as indicated by the 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 northeastern margin of the Paradox Basin.

Madera Limestone

During deposition of the Paradox and Honaker Trail Formations, carbonates of the Madera Limestone were deposited in the southeastern part of the basin. Southeast of the evaporite facies of the Paradox, equivalent rocks are composed of mixed carbonate beds and shale marker beds. The Paradox sequence of cyclically bedded deposits has a distinctive geophysical-log response that was traced as far as possible to the eastern and southern parts of the basin. The term Madera Limestone was used where the cyclic beds could no longer be recognized.

The Madera Limestone was named for exposures in the Sandia Mountains, near Albuquerque, N. Mex., by Keyes (1903). In the Nacimiento Mountains Wood and Northrop (1946) divided the unit into a lower gray limestone member and an upper arkosic member. The maximum recorded thickness of the Madera Limestone in the subsurface of the study area is 1,290 ft (393 m). The thickness of the Madera and equivalent rocks of the combined Paradox and Honaker Trail Formations is shown on plate 7.

The gray limestone member is composed of dark-gray, locally cherty limestone interbedded with arkosic sandstone and gray, fossiliferous shale (Wood and Northrop, 1946). Beds are from a few inches to a few feet thick (DuChene, 1974, p. 161). In some places in the Nacimiento Mountains the member conformably overlies the Sandia Formation, but in other places it unconformably overlies Precambrian rocks (Woodward, 1987, p. 25). In the northern and western Nacimiento Mountains the gray limestone member is absent (DuChene, 1974, p. 161).

The arkosic member is composed of gray arkosic limestone, pink arkose, red or brown arkosic sandstone, and fossiliferous, calcareous shale (Jentgen, 1977, p. 130; Woodward, 1987, p. 24). The percentage of arkose increases upward in the unit, and arkose is the dominant lithology at the top (DuChene, 1974, p. 161). The arkosic member conformably overlies the gray limestone member where the lower member is present; where the gray limestone member is not present the arkosic member overlies Precambrian rocks (Woodward, 1987, p. 25). On the northwestern side of the Nacimiento Mountains the Madera Limestone is absent (DuChene, 1974, p. 161; Woodward, 1987, p. 22).

Contact relations of Pennsylvanian rocks with overlying strata have been the subject of debate in other parts of the basin. In the Nacimiento Mountains Woodward (1987, p. 27) stated that "* * *the contact between the [Permian] Abo and the Madera is gradational with much intertonguing of beds." Woodward (1987) included this interval of intertonguing in the Madera and considered it as Pennsylvanian in age. The interval is included in the Abo Formation by J.L. Ridgley (U.S. Geological Survey, written commun., 1990) and by us.

Pennsylvanian and Permian Rocks

In the San Juan Basin and vicinity, a sequence of carbonate and clastic rocks is transitional between underlying dominantly marine strata and overlying continental strata and in many places approximately marks the Pennsylvanian-Permian boundary. In the northern San Juan Basin this sequence was named the Rico Formation and was considered both Pennsylvanian and Permian in age (Cross and Spencer, 1900). The same age was assigned to the Rico in the Monument upwarp by O'Sullivan (1965, p. 32). In the Nacimiento Mountains this carbonate and clastic sequence was included in the upper part of the Madera Limestone and was considered Pennsylvanian in age (Woodward, 1987). Southeast of the San Juan Basin a similar sequence above the Madera comprises the Bursum Formation, which is considered Permian in age (Rascoe and Baars, 1972). Northwest of the San Juan Basin, in the Paradox Basin, Baars (1962) named a perhaps comparable rock sequence the Elephant Canyon Formation, which he considered Permian in age.

In this study we identified a widespread interval of interbedded limestone, sandstone, mudstone, and shale transitional between the Hermosa and the overlying Cutler. The unit has a readily identifiable geophysical-log response and could be mapped through most of the San Juan Basin (pl. 8). No new data were collected in this study that aid in determining the age of the Rico, although it is likely time transgressive across the area of the basin. As clastics were shed from the highlands to the north and gradually displaced marine water from the basin, the sequence of intertonguing carbonate and clastic rocks would have tended to rise stratigraphically toward the basin center and would have crossed time lines. For this reason, we do not include the Rico in either the Pennsylvanian or the Permian; maps showing the thicknesses of these systems exclude the Rico.

The Rico Formation was named for exposures near the Rico Mountains at Rico, Colo. (Cross and Spencer, 1900, p. 59). Near Rico the formation consists of conglomeratic sandstone and arkose interbedded with greenish-, reddish-, and brownish-gray shale and sandy fossiliferous limestone (Pratt, 1968, p. 85). The Rico was originally defined by Cross and Spencer on the basis of its fossil content of Pennsylvanian and Permian invertebrates, not by an easily mappable lithology, and its thickness was estimated as 325 ft (99 m). It was considered to be a unit transitional between the underlying marine Hermosa Group and the overlying continental Cutler Group. In the study area this unit attains a maximum thickness of about 275 ft (84 m) in southeastern Utah and southwestern Colorado. A band of thick Rico parallels the Colorado–New Mexico State line eastward toward Pagosa Springs (pl. 8). Another thick area trends southeastward toward Albuquerque.

An important consideration regarding regional recognition of the Rico is the nature of the Pennsylvanian-Permian boundary. Baars (1962, fig. 4) interpreted the boundary as conformable in most of the San Juan Basin but unconformable on the western side of the basin and in much of southeastern Utah. Figure 5 herein, which is oriented northeast-southwest, shows thinning of the Pennsylvanian section southwestward from the San Juan trough to the Zuni-Defiance positive area; however, the thinning probably is within the Paradox and Honaker Trail Formations, not in the unit identified as Rico as suggested by Baars (1962). The unit we identify as the Rico continues southward across the area and apparently was not beveled by pre-Permian erosion. Likewise our figure 6, which is oriented northwest-southeast, also crosses the boundary between the areas of continuous sedimentation and erosion as shown by Baars (1962). In figure 6, Pennsylvanian strata actually thicken northwestward in the direction of the area of presumed erosion.

These cross sections indicate little about the age of the Rico or underlying strata in the San Juan Basin. They do, however, show that a lithostratigraphic unit consisting of mixed carbonate and clastic beds is continuous across an area that has been interpreted to have undergone erosion. On figures 5 and 6 this erosion is not evident. In the San Juan Basin the Rico is a mappable lithostratigraphic unit that is present in most parts of the basin. Continuing studies will attempt to show the physical extension or the truncation of this stratigraphic interval northwestward into east-central Utah. Key questions about this unit concern the nature of the change from marine to continental rocks, the presence or absence of a significant unconformity in the sequence, and its position relative to the Pennsylvanian-Permian boundary.

Permian Rocks

Permian rocks in the San Juan Basin are assigned to the Cutler Group (0–2,455 ft, 0–748 m), Abo Formation (250–675 ft, 76–241 m), Supai Formation (450–755 ft, 137–230 m), Yeso Formation (15–525 ft, 4.5–160 m), Glorieta Sandstone (75–300 ft, 23–91 m), and San Andres Limestone (0–195 ft, 0–59 m). The Bernal Formation, a lateral facies equivalent of the San Andres that is recognized in outcrop in the southern Nacimiento Mountains (Woodward, 1987, p. 30), was not distinguished as a separate unit in this study. The total Permian section is 0–2,455 ft (0–748 m) thick (pl. 9). The nomenclature adopted here, recognizing the Cutler as a group, is after Wengerd and Strickland (1954) and Baars (1962). The Cutler has also been considered a formation with constituent members (O'Sullivan, 1965), but these members have the lithic characteristics and mappability required of a formation as defined in the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983).

Near the Uncompahgre uplift the Cutler is considered to be a single undivided unit of formation rank; however, south and southwest of the uplift it attains group status and is divided into several formations with gradational contacts that are distinguished lithologically. These formations are, from oldest to youngest, the Halgaito Formation (0–1,005 ft, 0–306 m), Cedar Mesa Sandstone (0–630 ft, 0–192 m), Organ Rock Formation (0–1,555 ft, 0–474 m), and De Chelly Sandstone. For this study the De Chelly was divided into lower and upper parts that are considered here to be equivalent to the Meseta Blanca Sandstone Member of the Yeso Formation and the Glorieta Sandstone, respectively. The lower part of De Chelly and Meseta Blanca is 0–555 ft (0–169 m) thick; the upper part of De Chelly and Glorieta is 0–360 ft (0–110 m) thick.

Cutler, Abo, and Supai Formations

The undivided Cutler Formation, named by Cross and others (1905, p. 5) for exposures along Cutler Creek near Ouray, Colo., 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 about 2,500 ft (762 m) was measured at outcrops 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. 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.

Rocks partly equivalent to the Cutler are the Abo Formation, which is recognized in the Nacimiento and Zuni Mountains, and the Supai Formation, which is recognized on the Defiance Plateau. Both the Abo and Supai are considered equivalent to the Halgaito Formation, Cedar Mesa Sandstone, and Organ Rock Formation of the Cutler Group. A thin tongue of the Supai that overlies the lower part of the De Chelly Sandstone on the Defiance Plateau is considered equivalent to the San Ysidro Member of the Yeso Formation.

The Abo Formation was named for exposures in Abo Canyon in the Manzano Mountains by Lee (1909). In the Zuni and Nacimiento Mountains the unit is composed of medium- to dark-brownish-red mudstone, siltstone, and arkosic sandstone. Thin beds of limestone have been reported at the base of the unit in the southern Nacimiento Mountains where it gradationally overlies the Madera Limestone (Woodward, 1987, p. 27); similar limestone beds are present in the lower part of the Abo in the Zuni Mountains (Smith, 1958; Smith and others, 1959; Goddard, 1966). The limestone beds in the Zuni Mountains may be Pennsylvanian in age (Smith, 1958; Smith and others, 1959; A.K. Armstrong, U.S. Geological Survey, oral commun., 1990). In the Zuni Mountains and locally in the northern Nacimiento Mountains the Abo rests unconformably on Precambrian rocks. In those areas the base of the Abo consists of arkosic conglomerate. The Abo gradationally overlies the Madera Limestone in the southern Nacimiento Mountains. The source of the Abo was the Uncompahgre highlands (Baars, 1962, p. 211); local sources were the Zuni and Peñasco uplifts (Woodward, 1987, p. 27).

Correlative rocks on the west side of the San Juan Basin were assigned to the Supai Formation by Read and Wanek, (1961). We continue to use this correlation but recognize that it is controversial and that other interpretations (Baars, 1962; Peirce and others, 1970; Blakey, 1979) have been made. On the Defiance Plateau the Supai consists of reddish-orange to yellowish-gray, fine-grained sandstone and reddish-brown mudstone, siltstone, and conglomeratic sandstone. Abundant well-preserved salt casts and a limestone bed, about 5 ft (1.5 m) thick, are present near the top on the western side of the basin (Condon, 1986). The Supai unconformably overlies the Precambrian on the Defiance Plateau. The source of the Supai is the Uncompahgre highlands (Baars, 1962, p. 211); a local source on the Defiance Plateau is indicated by conglomerate beds at the base composed of clasts of the underlying Precambrian rocks.

Cutler Group

Halgaito Formation

The Halgaito Formation was named by Baker and Reeside (1929, p. 1421) for Halgaito Springs on the Monument upwarp (west of Comb Ridge, fig. 1). The unit consists of reddish-brown to dark-brown silty 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. In the northeastern part of the study area the unit is erosionally truncated by overlying Triassic rocks. Throughout most of the San Juan Basin the Halgaito conformably overlies the Rico Formation. In the subsurface the Halgaito is thickest in a southeast-trending lobate area that parallels the depositional center established in the Pennsylvanian (pl. 10). The maximum recorded thickness of the Halgaito in the study area, 1,005 ft (306 m), is just west of Cortez, Colo.

The Halgaito consists of alternating beds of marginal-marine mudflat and fluvial sediments that were deposited near sea level (Baars, 1962, p. 169). Murphy (1987) described loess deposits west of Comb Ridge (fig. 1). O'Sullivan (1965, p. 36) interpreted the Halgaito in the area just east of Comb Ridge to have been deposited in a restricted-marine basin on the basis of interbedded gypsum or anhydrite in that area.

Cedar Mesa Sandstone and Related Rocks

The Cedar Mesa Sandstone was originally described in the area 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 a facies change eastward in the unit near Comb Ridge (fig. 1) to a sequence of pastel siltstone and shale and lesser amounts of gypsum, sandstone, and limestone. 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 Formation.

For this study, the evaporite facies of the Cedar Mesa was correlated in the subsurface into southwestern Colorado, northeastern Arizona, and northwestern New Mexico. Well logs were examined from Comb Ridge eastward, and the evaporite unit is traceable as a distinctive lithologic unit on the logs. Evaporites are recorded in cuttings from this interval as far east as the Hogback monocline (pl. 11), where the unit is composed of four or more coarsening-upward sandstone and shale cycles recognizable throughout most of the San Juan Basin. By differentiating the Cedar Mesa in the San Juan Basin, it is also possible to map the extent of the underlying Halgaito and overlying Organ Rock Formations.

The Cedar Mesa is thick in the northwestern part of the study area (pl. 11); however, the locus of deposition probably is farther southwest than that of the underlying Halgaito Formation (pl. 10). The Cedar Mesa is erosionally truncated in the northeastern part of the study area. In the southwestern part of the basin the Gallup sag accumulated more sediment during deposition of the Cedar Mesa than it had during deposition of the Halgaito. 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). Sandstone beds and one bed of reworked gypsum that display large-scale crossbedding characteristic of eolian dunes were observed by us near Comb Ridge in southeastern Utah. In the northern San Juan trough the Cedar Mesa grades laterally into fluvial deposits; southward the Cedar Mesa grades laterally into the Abo Formation.

Organ Rock Formation

The Organ Rock Formation was named by Baker and Reeside (1929, p. 1422) for Organ Rock spire in Monument Valley. The Organ Rock is similar to the Halgaito 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 San Juan Basin in Utah (O'Sullivan, 1965, p. 46). Thickness trends of the Organ Rock parallel the Cedar Mesa only in part. The Organ Rock is relatively thick in southeastern Utah but thins in the Barker dome area at the Colorado–New Mexico State line (fig. 1, pl. 12). Another thick lobe is present in the eastern part of the basin. The unit is anomalously thick in a section north of Durango (pl. 12), but Baars (1962, p. 166) showed that the entire Cutler thickens markedly northwest of Durango (pl. 12), reflecting a source in the Uncompahgre highlands to the north. The Organ Rock is composed of coastal-plain, mudflat, loess, and fluvial deposits. In most of the basin the Organ Rock is characterized by a thick, sandstone-dominated fluvial sequence in about the middle of the unit that is overlain and underlain by mudstone-dominated strata.

De Chelly Sandstone and Related Rocks

The De Chelly Sandstone was named by Gregory (1917, p. 32) for exposures at Canyon De Chelly (east of Chinle) in northeastern Arizona (fig. 1). On the western side of the San Juan Basin the De Chelly is a tan, reddish-brown, and orangish-red, very fine to medium grained sandstone. The De Chelly is very thick bedded, exhibits large-scale, high-angle crossbeds, and has been interpreted as an eolian deposit (Peirce, 1967). The unit conformably overlies the Supai Formation on the Defiance Plateau and the Organ Rock in other parts of the San Juan Basin.

We divided the De Chelly into upper and lower parts based on geophysical-log response. This division corresponds to the separation of the De Chelly into two parts by Read and Wanek (1961) on the basis of stratigraphic position and sediment transport directions. The lower part has transport directions to the southeast and the upper part to the southwest (Read and Wanek, 1961, p. H5).

We correlated the lower part of the De Chelly with the Meseta Blanca Sandstone Member of the Yeso Formation (of the Nacimiento Mountains) and the upper part of the De Chelly with the Glorieta Sandstone. A southward-thickening wedge of sandstone, siltstone, limestone, and evaporites, the San Ysidro Member of the Yeso Formation, lies between the Meseta Blanca and the Glorieta. A similar southward-thickening tongue of the Supai Formation separates the lower and upper parts of the De Chelly Sandstone on the Defiance Plateau. This interpretation differs somewhat from that of Baars (1962, p. 182), who correlated the entire De Chelly Sandstone with the Meseta Blanca and considered the Glorieta Sandstone as younger than any part of the De Chelly.

Plate 13 shows the thickness of this entire interval of equivalent rocks (upper and lower parts of De Chelly Sandstone, Meseta Blanca Sandstone and San Ysidro Members of the Yeso Formation, and Glorieta Sandstone). The interval is thickest on the Defiance Plateau, where the De Chelly thickens, and in the southeastern part of the study area, where the San Ysidro Member thickens southward. The interval pinches out northward, both by gradation into the undivided Cutler Formation and by pre-Chinle erosion.

Plates 14 and 15 show the thickness of the lower part of De Chelly and the Meseta Blanca and the upper part of De Chelly and the Glorieta, respectively. The unit identified as Meseta Blanca in the Zuni Mountains is considered by us as a local eolian sandstone accumulation in the Organ Rock and Abo interval (Huffman and Condon, in press) and was not included on the map with the lower part of De Chelly and the Meseta Blanca of the Nacimiento Mountains.

Yeso Formation

The Yeso Formation is divided into the Meseta Blanca Sandstone Member and the San Ysidro Member in the southern and eastern San Juan Basin. The Yeso was originally named by Lee (1909) for exposures at Mesa del Yeso, south of the San Juan Basin, and the members discussed here were named by Wood and Northrop (1946) for locations in the southern Nacimiento Mountains. The Yeso conformably overlies the Abo Formation.

Meseta Blanca Sandstone Member

The type Meseta Blanca Sandstone Member is composed of reddish-orange, fine- to medium-grained, well-sorted sandstone. The unit displays large-scale crossbeds and flat-bedded strata considered characteristic of eolian deposits (Stanesco, 1989). The Meseta Blanca is recognized in the southern Nacimiento Mountains and in the subsurface north of the Zuni Mountains.

Our subsurface correlations indicate that the Meseta Blanca of the Zuni Mountains lies stratigraphically below the type Meseta Blanca of the Nacimiento Mountains. The Meseta Blanca of the Nacimiento Mountains can be traced southwestward, and in the scattered drill holes north of the Zuni Mountains both units are present and are separated by fine-grained rocks of the Organ Rock or Abo Formation. The type Meseta Blanca pinches out southward and is not present in the Zuni Mountains. The control points in this part of the basin are too widely scattered to determine if the Meseta Blanca of the Zuni Mountains is an isolated time-correlative lens or a lower tongue of the Meseta Blanca of the Nacimiento Mountains.

Baars (1962, p. 191) noted that the Meseta Blanca of the Nacimiento Mountains is lithologically identical with and has the same style of crossbedding as the De Chelly Sandstone of the Defiance Plateau area, but that the Meseta Blanca of the Zuni Mountains is a flat-bedded, thin-bedded, very fine grained sandstone or siltstone. Stanesco (1989) reported that in the northern exposures (Nacimiento Mountains) wind transport directions of the Meseta Blanca are to the south and in southern outcrops (Zuni Mountains and Lucero Mountains) to both the north and south. These differences in lithology and transport directions lend support to our interpretation that the unit in the Zuni Mountains is distinct from the type Meseta Blanca of the Nacimiento Mountains. An alternative interpretation is that the Meseta Blanca of the Zuni Mountains is a lower tongue of the type Meseta Blanca and that it undergoes a facies change southward. The change could be from an erg sequence in the Nacimiento Mountains to marginal-marine deposits in the south (Stanesco, 1989).

San Ysidro Member

The San Ysidro Member consists of reddish-brown, fine-grained, evenly bedded, gypsiferous sandstone and siltstone and interbedded medium-gray limestone. On geophysical logs the limestone beds form conspicuous markers that are useful in making regional correlations. The member was deposited in a restricted-marine basin in environments that include eolian dune and sand sheet, coastal sabkha, tidal, and shallow shelf (Stanesco, 1989). Stanesco (1989) reported a cyclic shifting of these facies at least twelve times during deposition of the San Ysidro. The northern limit of deposition of the San Ysidro Member in the San Juan Basin approximates the northern edge of the sea.

Glorieta Sandstone

The Glorieta Sandstone was named by Needham and Bates (1943) for exposures at Glorieta Mesa, southeast of Santa Fe, N. Mex., and was recognized by Wood and Northrop (1946) in the Nacimiento Mountains. The Glorieta is buff to white, fine- to medium-grained, siliceous sandstone. The unit is evenly bedded in 2–6-ft (0.6–1.8 m)-thick beds that are crossbedded. Thicknesses of 75–195 ft (23–59 m) were recorded in the study area (pl. 15). Baars (1962, p. 198) interpreted the Glorieta as a mixed subaqueous and eolian deposit. The Glorieta conformably overlies the Yeso Formation and is correlated with the upper part of the De Chelly Sandstone on the basis of stratigraphic position and geophysical-log response (fig. 4).

San Andres Limestone and Bernal Formation

The San Andres Limestone was named by Lee (1909) for exposures in the San Andres Mountains of central New Mexico. In the western Zuni Mountains the unit consists of medium-gray to light-brown, thick-bedded limestone and dolomite interbedded with orange to white, fine- to coarse-grained sandstone, pink siltstone, and purple shale (Baars, 1962, p. 203). In the eastern Zuni Mountains the unit is mainly composed of carbonate rocks (Baars, 1962, p. 208). In the southern Nacimiento Mountains the San

Andres passes laterally into redbeds, and the sequence is known as the Bernal Formation (Woodward, 1987, p. 30). The Bernal was not picked as a separate unit in this study because its geophysical-log response is indistinguishable from basal Triassic strata. The San Andres is recognizable in about the southern half of the San Juan Basin (pl. 16). The pinchout line shown on plate 16 is thought to be primarily due to postdepositional erosion but may be due in part to gradation northward into Bernal-type redbeds. The San Andres is as thick as 195 ft (59 m). It was deposited in a marine basin that deepened to the south of the present San Juan Basin.

Post-Permian Rocks

Permian rocks of the San Juan Basin are unconformably overlain by the Lower and Middle(?) Triassic Moenkopi Formation or the Upper Triassic Chinle Formation. Strata referred to the Moenkopi(?) Formation were described in the Zuni Mountains by Stewart and others (1972, p. 26). The Moenkopi(?) is irregularly distributed in the Zuni Mountains and is not present in the Nacimiento Mountains. Pre-Moenkopi channels as deep as 50 ft (15 m) were cut into and locally through the San Andres Limestone in the northern Zuni Mountains. These channels were filled with strata of the Moenkopi(?) Formation. In some areas karst topography developed on top of the San Andres prior to deposition of the Moenkopi(?) Formation. Stewart and others (1972, p. 25) recognized the Holbrook Member of the Moenkopi in the southern Defiance Plateau. This unit overlies the upper part of the De Chelly Sandstone at a sharp, but not obviously channelled, contact.

Farther north on the Defiance Plateau the Moenkopi is cut out by the Chinle Formation near Hunters Point (Condon, 1986). The Chinle overlies Permian rocks northward on the Defiance Plateau and in the Nacimiento Mountains. In the northern part of the basin the correlative Dolores Formation overlies Permian rocks. In the Piedra River area Permian strata are erosionally truncated by the Dolores (Condon and others, 1984).

TECTONIC AND STRUCTURAL FRAMEWORK

The purpose of this discussion is to describe the general tectonic framework within which Pennsylvanian and Permian structures in the vicinity of the San Juan Basin evolved and then to discuss those structures in some detail.

The tectonic mechanism for the development of the Ancestral Rocky Mountains and the related basins such as the Paradox Basin and San Juan trough is not yet clear. Recent workers such as Dickinson (1981), Kluth and Coney (1981), Kluth (1986), and Budnik (1986) related this intracratonic orogenic activity to the Pennsylvanian and Early Permian collision between Gondwana and Laurentia that produced the Appalachian, Ouachita, and Marathon fold and thrust belts (fig. 7). The principal objection to this thesis, as pointed out by Warner (1983), among others, is that the physical properties of the crust do not allow transmission of stress over such long distances. Shearing along existing zones of weakness, as for instance the Southern Oklahoma aulacogen (Hoffman and others, 1974), expressed in continental-scale lineaments, has been suggested as a possible explanation of such apparent contradictions (Donath, 1964; Kluth and Coney, 1983). For example, Sales (1968) interpreted the Texas, Wichita, and Lewis and Clark lineaments (fig. 7) as megashears, Warner (1978, 1980) discussed wrench faulting along the Colorado lineament, and Baars and Stevenson (1981) called on movement along these large shear zones to produce the Paradox Basin and San Juan trough. Even though many workers now agree that some of these lineaments demonstrated some degree of strike-slip movement in the Pennsylvanian and Permian, there is little agreement as to the magnitude, direction of motion, or importance of these movements.

The most persuasive lines of evidence relating the formation of the Ancestral Rocky Mountains and associated basins to the events on the eastern and southeastern margins of North America are the modern analog of the India-Asia collision (Tapponnier and Molnar, 1976), the close similarity in timing between the late Paleozoic collisional events and the uplifts, and the apparent absence of any other causal mechanism. Tapponnier and Molnar (1976) demonstrated, both empirically and theoretically, that significant stress can be transmitted long distances from convergent continental margins along shear zones in the crust, resulting in uplifts and associated basins more than 2,000 mi (3,200 km) from the suture zone. The Ancestral Rocky Mountains extended from the vicinity of the Ouachita and Marathon thrust belts approximately 800 mi (1,290 km) northwest and north (Budnik, 1986; Lindsey and others, 1986) to the area of the Pathfinder uplift (fig. 3). The Uncompahgre uplift is approximately 1,500 mi (2,400 km) west of the contemporaneous Southern Appalachian orogenic belt. Both of these distances are significantly less than the Asian examples documented by Tapponnier and Molnar (1976).

The strongest circumstantial argument for a cause and effect relationship between the continent-continent collisions along the eastern and southeastern margins of North America and the intracratonic deformation resulting in the Ancestral Rocky Mountains is their age equivalence. Tectonic activity in the area of the Ancestral Rocky Mountains began in the Late Mississippian, reached its greatest

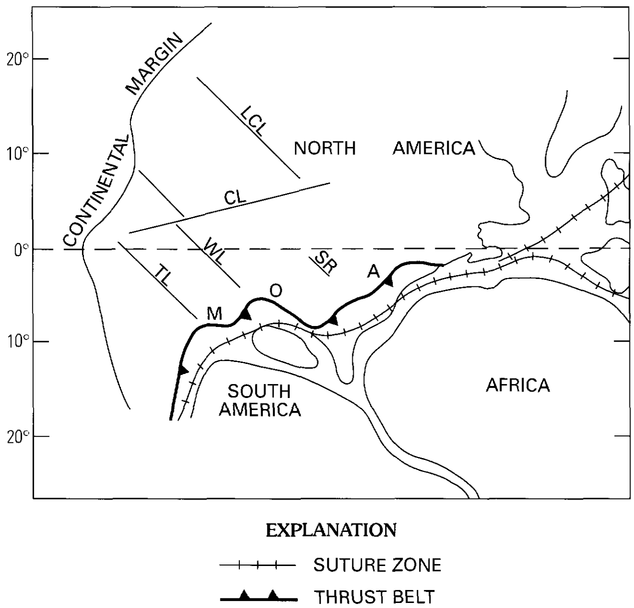


Figure 7. Configuration of plates during late Paleozoic time. Symbols: A, Appalachian belt; M, Marathon belt; O, Ouachita belt; CL, Colorado lineament; LCL, Lewis and Clark lineament; SR, Shawneetown–Rough Creek fault; TL, Texas lineament; WL, Wichita lineament. Modified from Sales (1968), Warner (1980), and Budnik (1986).

intensity in the Middle Pennsylvanian (Desmoinesian), and died out in the Early Permian (Wolfcampian or Leonardian), at the same time as the cessation of thrusting along the southeastern continental margin (Kluth and Coney, 1981). The close correspondence in timing between this sequence of events and the strongly compressive orogenic activity in the southern Appalachians (Rodgers, 1967; Hatcher, 1972) and the Ouachita-Marathon region (Ham and Wilson, 1967; Thomas, 1976) has led many workers to the conclusion that the three are closely related.

The absence of any other demonstrable source of the necessary stresses led Burchfiel (1979) and Dickinson (1981) to argue for the forces to have originated in the east and southeast. The western margin of the North American plate was thought to have been quiescent from the end of the Antler orogeny (Early Mississippian) to the initial deformation of the Sonoma orogeny (Late Permian). As Goldstein (1981) correctly pointed out, however, there are significant differences between the Asia-India collision and the inferred North America–South America collision in the Ouachita-Marathon region. Some of these differences led Budnik (1986) to the conclusion that the principal source of stress was the segment of the Gondwana-Laurentia collision that produced the southern and central Appalachians. Recent work by Stone and Stevens (1988) and Stevens and Stone (1988) led them to postulate Pennsylvanian-Permian wrench faulting along the western margin of North America. Their thesis suggested to Smith and Miller (1990) that structural development of the Ancestral Rockies may reflect the overlapping influences of both the extensional and compressional margins.

As elsewhere in the Ancestral Rocky Mountains, there is general agreement on the timing of deformation in the area of the San Juan trough but some disagreement on the style. Rapid uplift of the Uncompahgre–San Luis highlands and related subsidence of the Paradox Basin–San Juan trough began in the Middle Pennsylvanian (Desmoinesian) and continued through the Early Permian (Wolfcampian or Leonardian). Throughout the Pennsylvanian the Defiance-Zuni platform was a relatively positive element but probably not always emergent. It was uplifted in the Early Permian so that parts of it contributed sediment to the trough through much of the Wolfcampian.

Tweto (1980) described the Pennsylvanian and Permian Uncompahgre uplift–San Luis highland as a cuesta with a steep normal fault on its southwestern side. DeVoto (1980) suggested that only vertical movement occurred on this fault and that the Picuris-Pecos fault along the eastern margin of the cuesta was also active. Stone (1977) indicated that the Garmesa fault on the northeastern margin and the Uncompahgre fault along the southwestern margin both demonstrate a degree of left-lateral movement in addition to the vertical movement. Frahme and Vaughan (1983) documented as much as 6 mi (9.6 km) of horizontal and 20,000 ft (6,100 m) of vertical displacement on the Uncompahgre fault in the northern Paradox Basin during the Middle Pennsylvanian to Early Permian. Stevenson and Baars (1986), summarizing the structural evolution of the Paradox Basin, argued for large amounts of right-lateral movement on the Uncompahgre–San Luis highlands faults. They also recognized significant left-lateral movement on a number of northeast-trending shear zones, including one beneath the Hogback monocline along the northwestern margin of the present-day San Juan Basin.

Huffman and Taylor (1989) documented Pennsylvanian and Permian movement on northwest- and northeast-trending faults in the San Juan trough but were unable to demonstrate any significant lateral motion. Displacement on the fault zone that underlies the Hogback monocline was generally down to the northwest, resulting in the accumulation of several hundred more feet of Hermosa and Cutler sediments on the Paradox Basin side (Taylor and Huffman, 1988). The geometry of this proposed fault is not well known.

The San Juan trough retained its general shape and character throughout most of the Pennsylvanian and Permian Periods. As can be seen on plates 2–16 there was a dominant northwest-southeast depositional trend, as well as several persistent northeast-southwest trends. These trends in the isopachs reflect a basement fault pattern that exerted some control on all or most rock units in the San Juan Basin (Stevenson and Baars, 1977, 1986; Huffman and Taylor, 1989). The mapped basement faults are subparallel with the northwest-trending Uncompahgre–San Luis highlands and the northeast-trending Hogback monocline (fig. 3). Many of the faults shown in figure 8 exhibit evidence of some vertical movement in the Pennsylvanian and Permian, but the amount of lateral movement, if any, is not known. What is apparent, however, is that these basement fractures, probably inherited from the Precambrian, have been a major factor in the development of the basin and its resources throughout its history.

The basement fault map (fig. 8) was constructed from a reflection seismic grid (A.C. Huffman, Jr., and D.J. Taylor, unpublished data) containing 1,105 mi (1, 780 km) of data. Gaps in the fault pattern in most cases are probably due to lack of data. No attempt was made to determine when and in what sense every fault segment moved; however, on most of the faults where movement history was determined, several episodes of activity could be measured and one or more reversals in direction of motion identified. It is also important to note that in this interpretation different segments of the same fault commonly demonstrate different movement histories. These two observations can be explained in several ways that are mostly dependent on the regional stress field. In a vertical tectonics environment, each of the blocks behaves somewhat independently, either rising, falling, or tilting to accommodate regional movements. In an environment dominated by compression, with or without significant shears, the various blocks would move both vertically and laterally relative to each other; thus their bounding faults would form an intersecting pattern, with varying senses of motion along their extent. Either scenario can be applied to the Paradox Basin–San Juan trough area during the Pennsylvanian and Permian. None of the evidence reported to date is conclusive; however, the Frahme and Vaughn (1983) analysis of the Uncompahgre fault argues strongly for a large component of southwest-directed compressive-transpressive stress.

The results of our study suggest that large blocks in the San Juan trough exerted significant control on deposition throughout the Pennsylvanian and Permian. One possible configuration of such blocks, the result of combining data from the isopach maps (pls. 2–16) and the basement fault map (fig. 8), is shown in figure 9. A complicating factor in this or any discussion concerning the size and effect or even existence of such structures is the distribution of data. As can be seen on plates 2–16 and figure 8, large gaps in both data sets leave ample room for alternate interpretations.

Pennsylvanian depositional patterns (pls. 2–8) strongly suggest that the northwest-southeast trend was dominant throughout deposition and that the north-central blocks were down (fig. 10*A*). The northeast-southwest trend was apparently less active, although the fault underlying the Hogback monocline was down to the northwest at various times throughout the period. Stevenson and Baars (1986) outlined a number of small blocks on the Four Corners platform that were active in the early Paleozoic. It is not known whether these were also active in the Pennsylvanian. Our well data indicate some thickening and thinning in this area that might reflect such movement, but we have insufficient seismic information to confirm the findings of Stevenson and Baars.

Thickness trends (pls. 9–16) indicate that the northeast-southwest trend was more active in the Permian. The blocks underlying the Four Corners platform, Blanding Basin, and Tyende saddle (fig. 2) were down during Halgaito and Cedar Mesa time as were the central blocks stretching from Gallup to Pagosa Springs (fig. 10*B*). The effects of these block movements diminished significantly higher in the stratigraphic section. The pattern in figure 9 could be viewed as indicating right-lateral movement on northeast-trending faults. This may or may not be the case, but in any event it would have to be considered as cumulative movement on zones of weakness inherited from the Precambrian and not necessarily due to Pennsylvanian or Permian activity alone. The present-day structural configuration (pls. 17, 18) reflects primarily Laramide deformation, but many of the same trends are evident.

PALEOGEOGRAPHY

Paleogeographic reconstructions of the San Juan Basin area during the late Paleozoic demonstrate the general constancy in shape and character of the San Juan trough. The principal variables throughout this time span were the heights of bounding uplifts and relative sea level. The paleoclimate was arid to semiarid in the lower elevations (Mallory, 1972). Only the large volume of organic material derived from the Uncompahgre and San Luis highlands during the Desmoinesian suggests the presence of dense vegetation. The only other indications of terrestrial vegetation are interdune and paleosol horizons containing rhizoliths and widely scattered petrified plant accumulations or imprints. Eolian or evaporitic conditions were established whenever land was subaerially exposed.

Cyclic sedimentation throughout the late Paleozoic was probably the result of eustatic fluctuations produced by southern Gondwana glaciation, modified by regional and local tectonics. The last transgression to fully cover the lowlands in the area was at the close of Honaker Trail time, although the full extent of the youngest Rico transgressions are unknown. Cyclicity during the Permian is well documented in marine and evaporite sequences south of the area (Mack and James, 1986) and is reflected in many of the eolian, fluvial, and evaporite deposits of the Paradox Basin and San Juan trough.

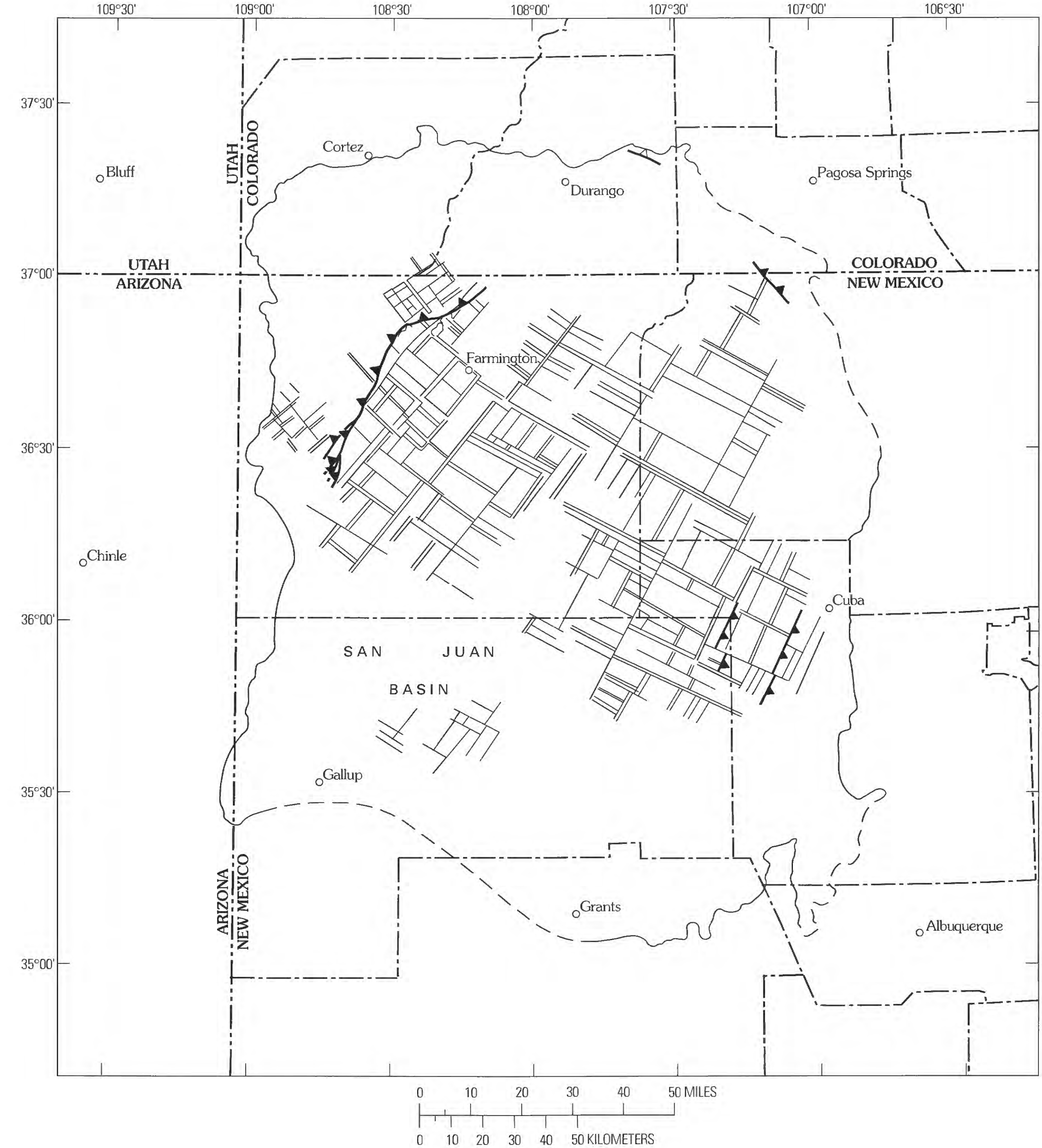


Figure 8. Basement faults of the San Juan Basin and adjacent areas. Large areas in which no faults are shown are areas for which seismic coverage was not available. Outline of basin based on outcrops of Dakota Sandstone (solid line) and structure (dashed line). Sawteeth on fault indicate thrust fault; sawteeth are on upper block. Modified from A.C. Huffman, Jr., and D.J. Taylor (unpublished data).

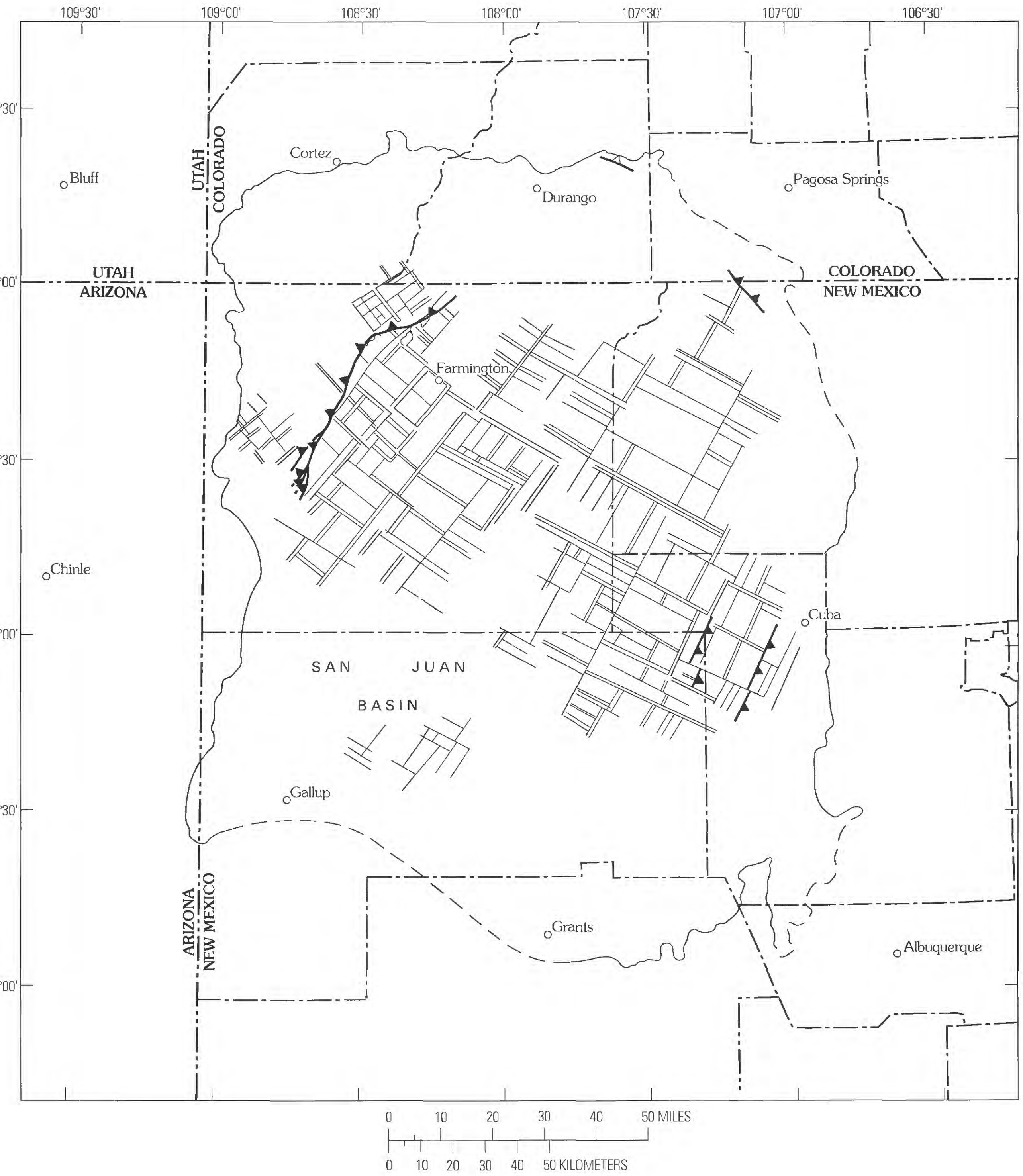
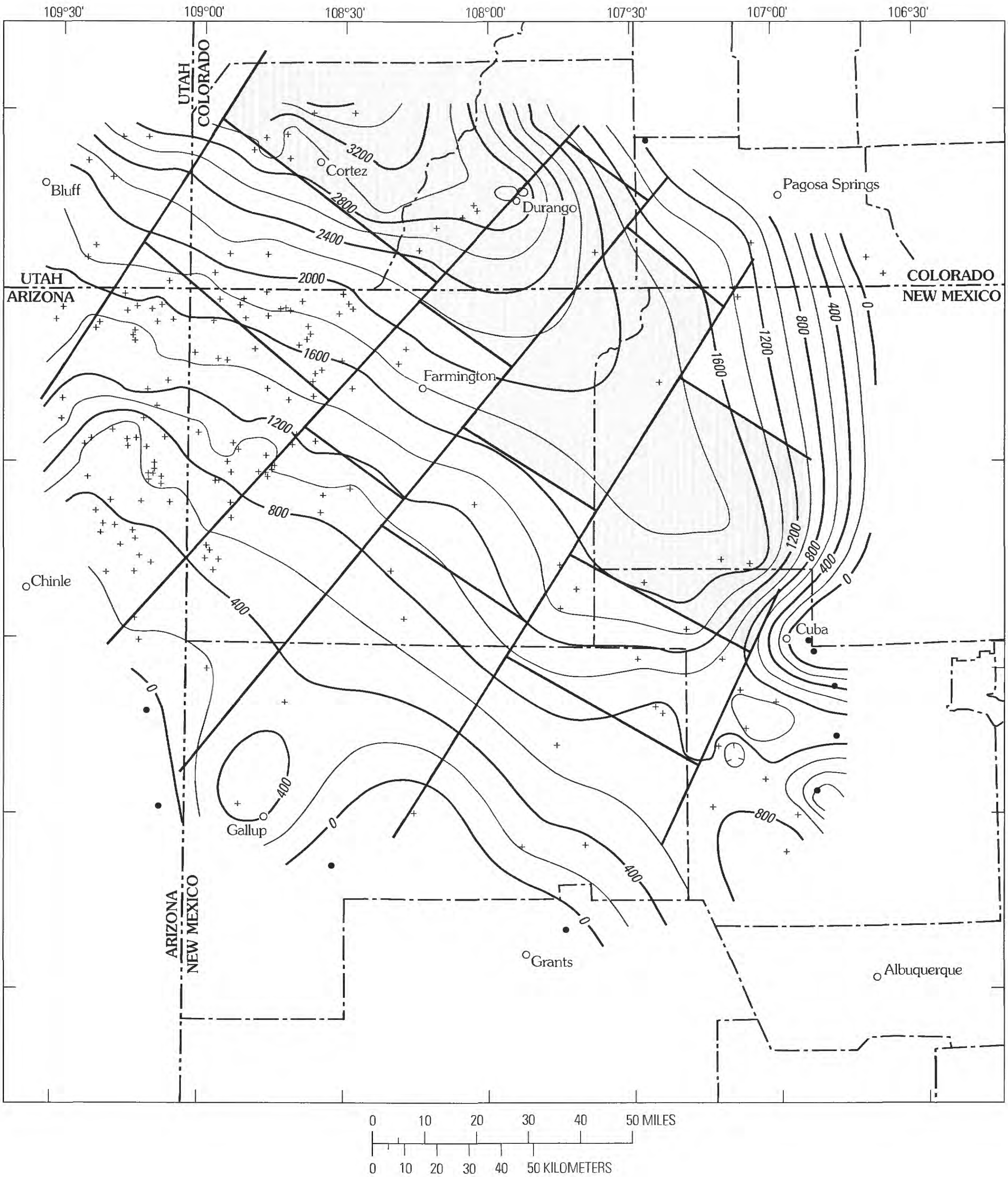


Figure 9. Hypothetical blocks controlling late Paleozoic deposition in the San Juan trough and adjacent areas. Map was produced by combining isopach data from plates 2–16 and basement fault data from figure 8. Northwesterly trending blocks probably exerted more influence in the Pennsylvanian and northeasterly trends more influence in the Permian. Sawteeth on fault indicate thrust fault; sawteeth are on upper block.



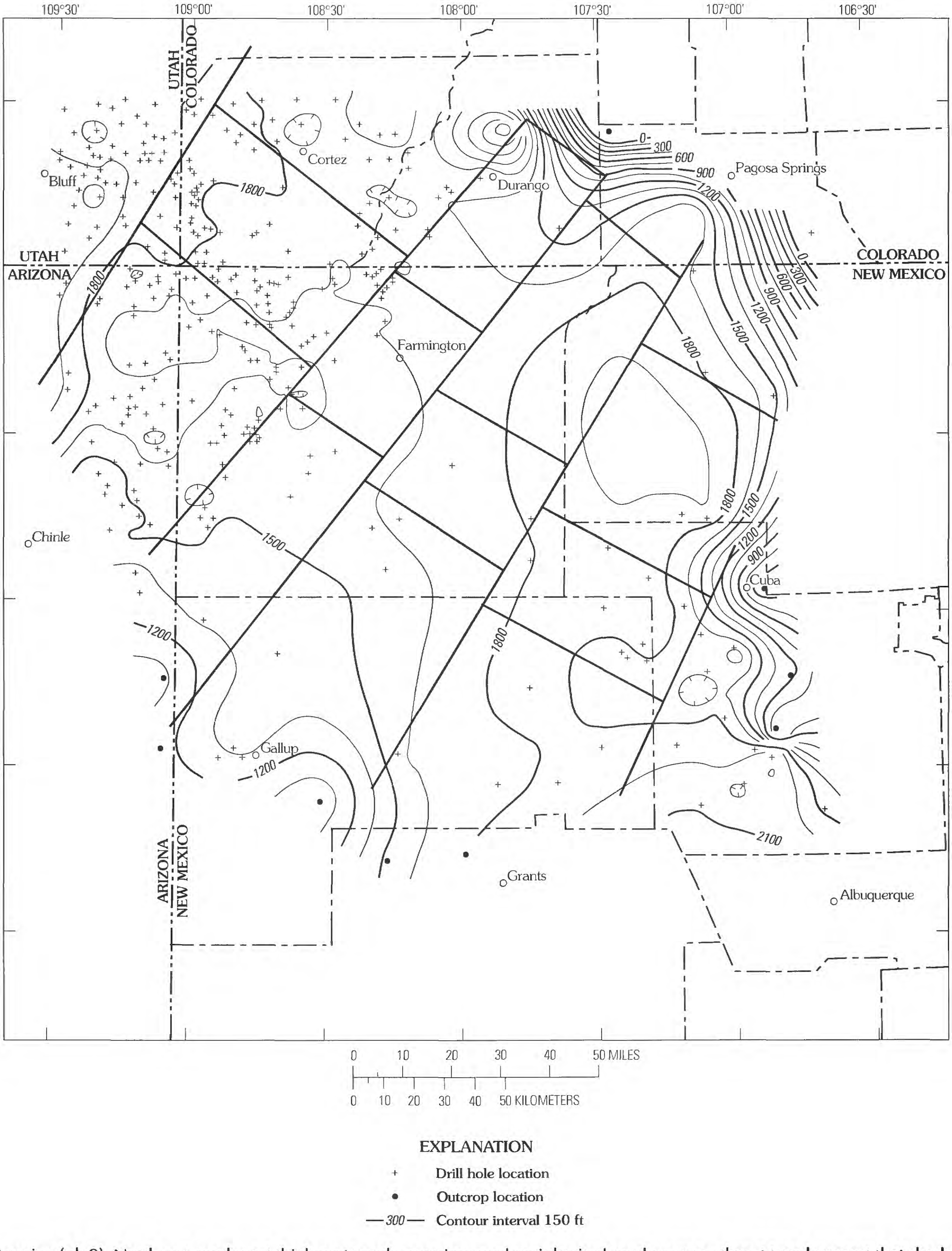
EXPLANATION

\+ Drill hole location

• Outcrop location

—400— Contour interval 200 ft

Figure 10 (above and facing page). Hypothetical blocks shown in figure 9 superimposed on total isopach maps. Location of drill holes shown by plus (+) symbol; location of outcrop sections shown by solid circle. *A*, Pennsylvanian (pl. 3). Dominant northwest-southeast thickness trend indicates that north-central blocks (shaded) were subsiding more rapidly than southwest blocks. Contour interval 200 ft.



B, Permian (pl. 9). Northeast-southwest thickness trends superimposed on inherited northwest-southeast trend suggest that shaded blocks were down and that northeast-trending faults were more active. Contour interval 150 ft.

We chose five approximate time slices to represent the variety of conditions present during the late Paleozoic. All five are variations on the same theme, the only major difference being the relative proportions of the various depositional environments. The time periods illustrated are Molas time (Chesterian to Morrowan, fig. 11*A*), mid-Paradox time (Desmoinesian, fig. 11*B*), Rico time (Pennsylvanian and Permian, fig. 11*C*), Cedar Mesa time (Wolfcampian, fig. 11*D*), and early De Chelly time (Leonardian, fig. 11*E*).

Each of the figures should be considered an approximation only because each is an average of many variations and details and neither absolute nor relative ages are well controlled in many parts of the section.

Molas Time (Chesterian to Morrowan)

At the close of the Mississippian (fig. 11*A*) the area occupied by the future San Juan Basin was exposed to subaerial erosion. A karst surface developed on the Mississippian Leadville Limestone along with a residual soil of unknown depth (Armstrong and others, 1980). In the earliest Pennsylvanian much of this soil horizon was reworked by streams flowing from the Uncompahgre and Defiance-Zuni uplands. Topography was subdued throughout the area, and the climate was probably equatorial with significant chemical weathering.

Paradox Time (Desmoinesian)

The Paradox Formation and related rocks were deposited during a time of rapid subsidence of the Paradox Basin and San Juan trough and rapid uplift of the Uncompahgre and San Luis highlands (fig. 11*B*). During periods of low relative sea level parts of the San Juan trough were either exposed or barely covered with very shallow water; recharge of normal marine water into the Paradox Basin thus was limited, and an enclosed evaporite basin formed. The Defiance-Zuni platform may or may not have been emergent; if emergent, it was a lowland that did not contribute much sediment. We did not show the Peñasco uplift along the southeastern margin of the trough as a separate major feature during any part of the Pennsylvanian as did Wengerd and Matheny (1958) or Szabo and Wengerd (1975), or even as a smaller feature such as suggested by Fetzner (1960), but rather followed Mallory (1972) and Bachman (1975) because our data do not indicate that the Peñasco uplift was necessarily emergent at any time before the Permian.

Peterson and Hite (1969, p. 894) considered the Hogback monocline area (fig. 2) to be the main accessway for circulation of normal marine water into the restricted waters of the Paradox Basin. Plate 5 and figure 6 show that the thickest part of the Paradox Formation is northwest of the Hogback monocline. Similar accessways on the north and west sides of the Paradox Basin were proposed by Wengerd (1962, p. 271).

Hite and Buckner (1981, p. 157) summarized mechanisms that may have controlled the cyclicity displayed by Paradox strata. One control is the interaction of sedimentation and subsidence rates. Assuming constant subsidence, the basin would have deepened gradually during times of slow sediment deposition of anhydrite, dolomite, and shale. During times of more rapid precipitation of halite the basin would have shoaled. A potential problem with this mechanism as the sole explanation is that the rate of subsidence probably was not stable for long enough periods of time.

Another possible control is local tectonism. The stratigraphy of the Paradox Formation shows that the Uncompahgre uplift was active at the time of its deposition. An abrupt facies change from carbonate and evaporite rocks of the Paradox to arkose on the northeastern margin of the basin indicates a strong tectonic influence. However, the marine accessways to the Paradox Basin and San Juan trough are thought to have been broad, shallow shelves that could have easily restricted the flow of normal marine water during eustatic falls in sea level, with or without any tectonic influence.

Fetzner (1960, p. 1396) noted that the Uncompahgre uplift was active from the Early Pennsylvanian through Permian time. His clastic ratio map of the Paradox indicates that a tremendous amount of clastic debris was shed into the basin from the uplift forming a delta that possibly blocked the southeastern part of the Paradox Basin. This delta would have affected circulation of marine water and could have caused periodic restriction of normal marine water. A similar barrier model proposed by Wengerd and Strickland (1954, p. 2186) calls on buildups of reef carbonate, in addition to clastic barriers such as submarine bars and outbuilding deltas, as restricting mechanisms. These mechanisms alone, however, could not have caused the repeated, somewhat regular depositional cycles in the trough as well as 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—plate-margin basins formed and filled due to collision between plates. Another type of cyclothem is marine-eustatic dominated and occurs in basins having only moderate tectonic influences. These cyclothems are probably 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. In such a model the

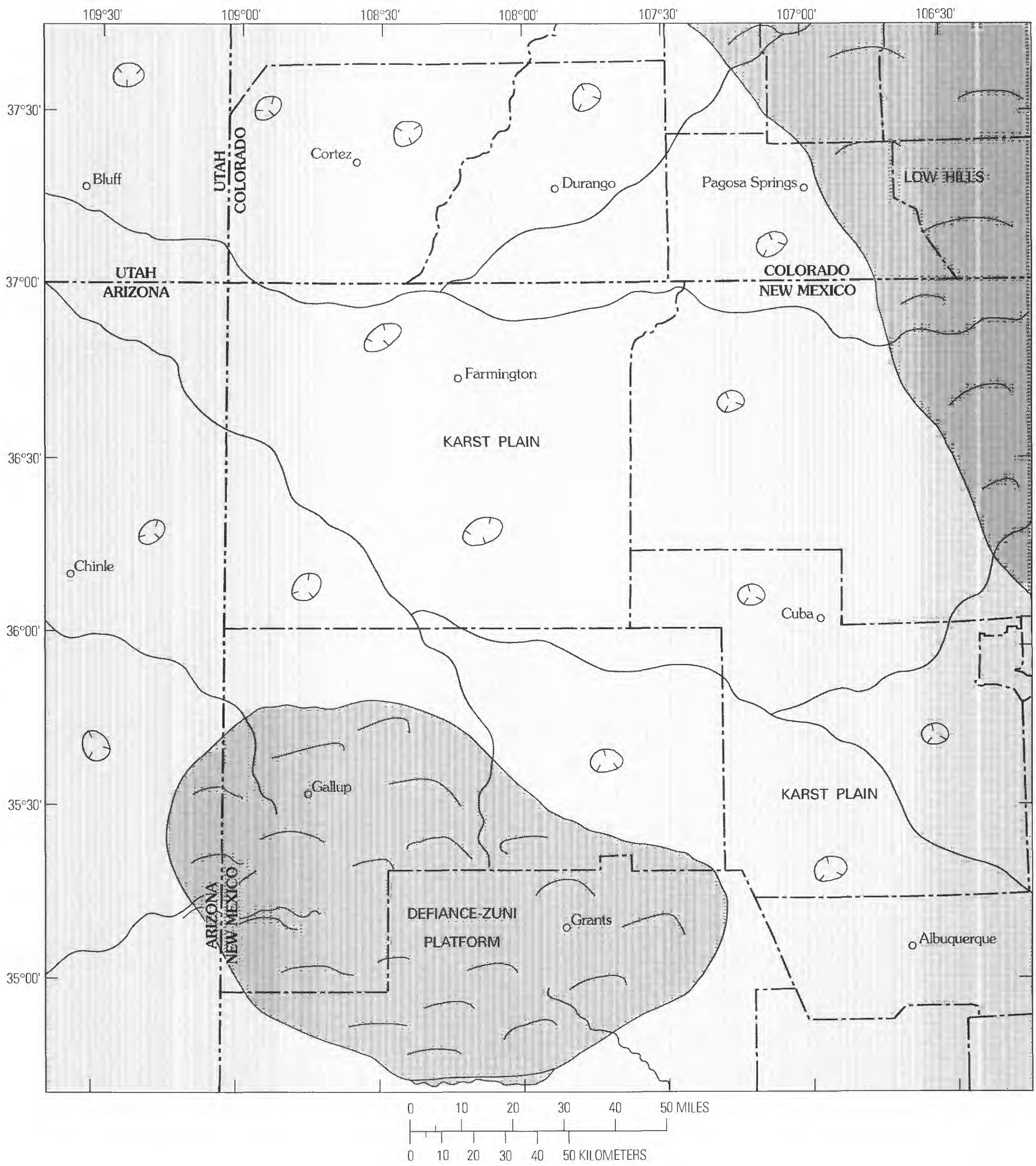


Figure 11 (above and following pages). Paleogeography of San Juan Basin and adjacent areas. *A*, Late Mississippian (Chesterian) to Early Pennsylvanian (Atokan) time during deposition of the lower to middle parts of the Molas and Log Springs Formations on Late Mississippian karst and erosion surface.

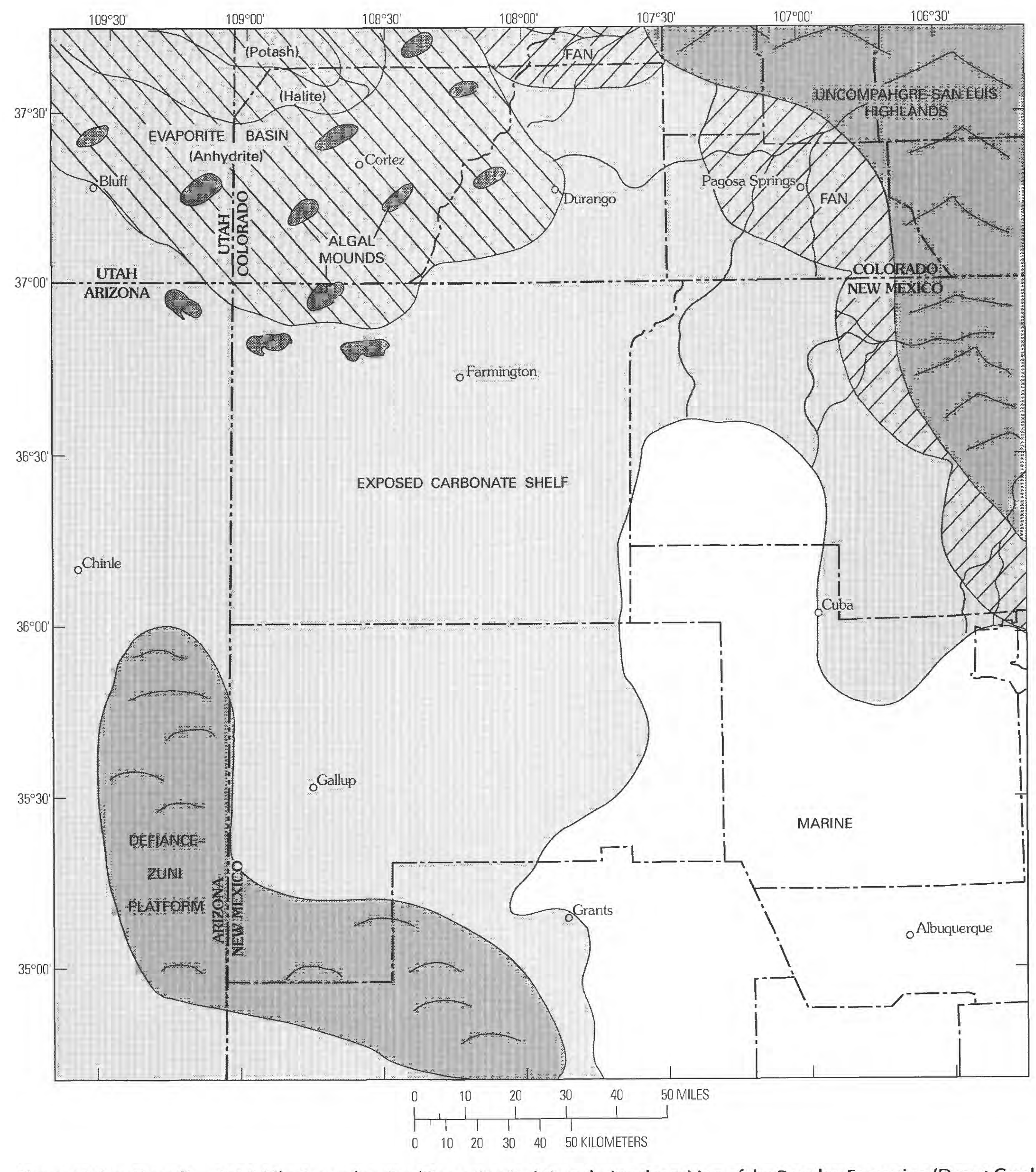


Figure 11 (continued). *B*, Middle Pennsylvanian (Desmoinesian) time during deposition of the Paradox Formation (Desert Creek time) and related rocks at time of maximum regression. The Defiance-Zuni platform was probably submerged during high stands.

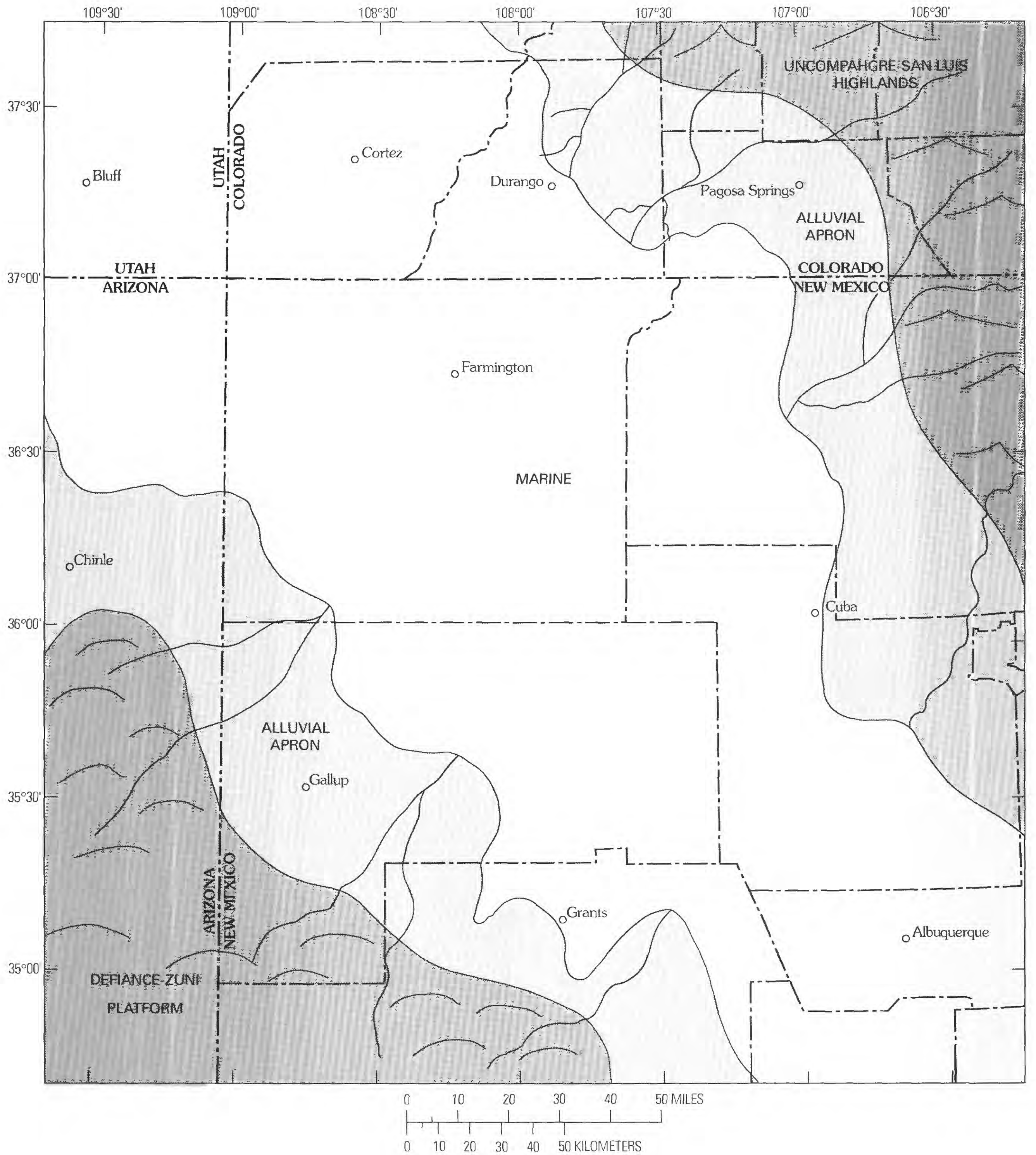


Figure 11 (continued). *C,* Late Pennsylvanian (late Virgilian) to early Permian (early Wolfcampian) time during deposition of the Rico Formation.

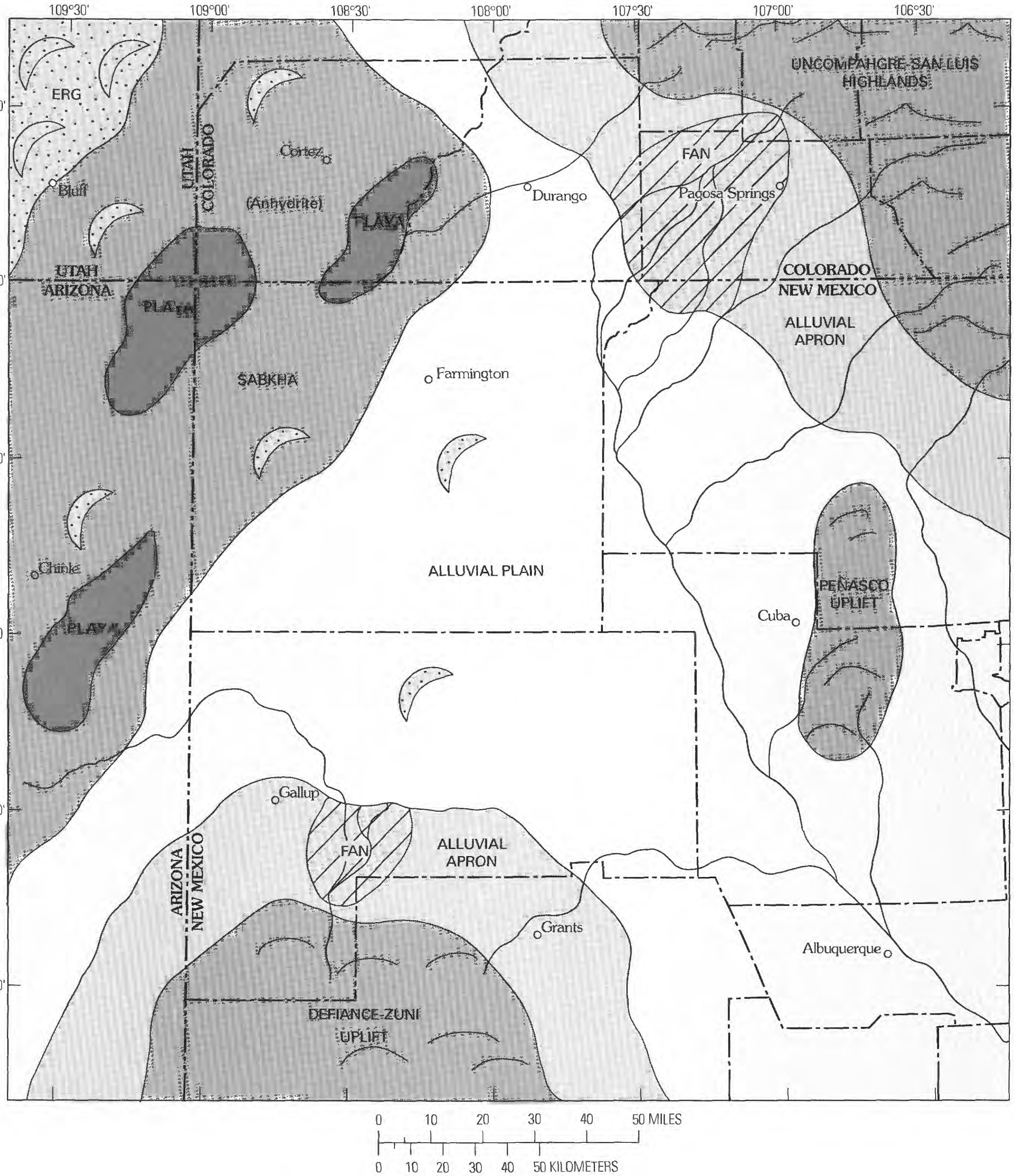


Figure 11 (continued). *D*, Early Permian (Wolfcampian) time during deposition of the Cedar Mesa Sandstone. A sabkha occupied the area of the downdropped Four Corners platform block.

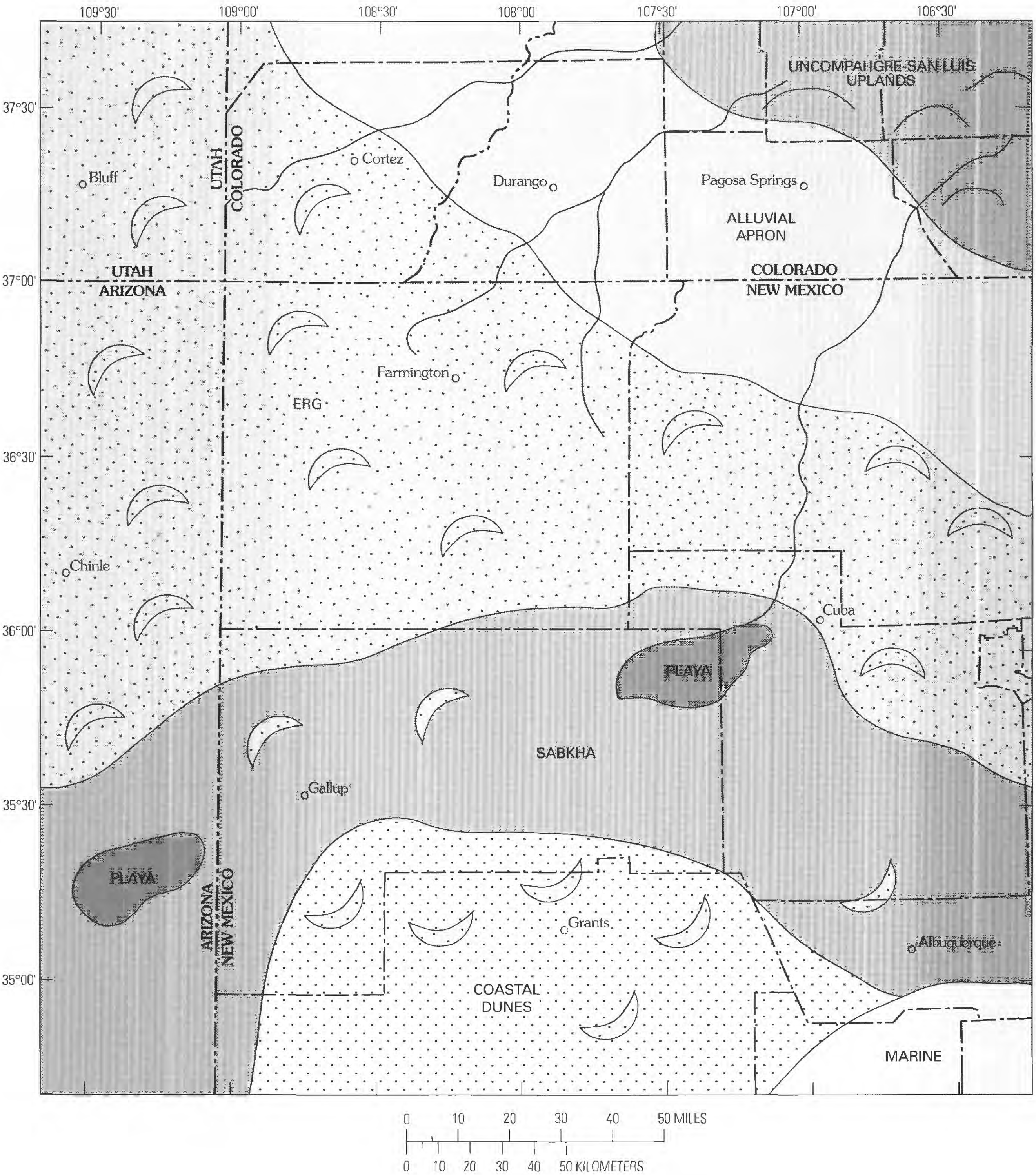


Figure 11 (continued). *E*, Early Permian (Leonardian) time during deposition of the lower part of the De Chelly Sandstone and the Meseta Blanca Member of the Yeso Formation. The Meseta Blanca of the Zuni Mountains is shown as an unconnected coastal dune field.

collision of Laurentia and Gondwana produced vertical uplift in the Uncompahgre highlands that provided large amounts of sediment to the subsiding basin. At the same time, global sea-level changes directly affected deposition in the area by periodically exposing the shelf areas, thus isolating the evaporite basin.

Implicit in the majority of discussions concerning eustatic controls is the idea that Pennsylvanian eustatic cycles were mostly dependent on climatic variations in the Southern Hemisphere. Missing from most models, however, is any consideration of local or regional climate variations. These effects may be difficult to distinguish but should be addressed in any comprehensive treatment.

Rico Time (Pennsylvanian and Permian)

The Rico Formation remains an enigma. As previously discussed, its age, extent, and precise lithology have not yet been completely determined. Because we have no new age data, the reconstruction shown in figure 11*C* is only an attempt to synthesize our lithologic observations and published data into a coherent picture.

The final transition from marine to continental deposition at any one location was controlled by eustatic changes, regional or local tectonism, an increase in the flood of detritus from the source areas, a change in subsidence rates, or some combination of the above. The earliest transitions generally would have been close to the highlands and the last tranisitions in the deep parts of the trough or nearest the sea, thus producing a time-transgressive but identifiable and mappable unit over the entire area. This generalized scenario could have been significantly modified by local tectonism so that on a growing salt dome or active fault block the character and timing of the transition to continental sedimentation might have differed significantly from that for a nearby lowland.

Cedar Mesa Time (Wolfcampian)

During Cedar Mesa time (fig. 11*D*) the Four Corners platform block (fig. 2) had subsided sufficiently to be invaded by marine waters from the south and form a coastal sabkha well into Utah (Stanesco and Campbell, 1989). Cyclic invasions of marine water resulted in deposition of anhydrite in the embayment and carbonate rocks on the alluvial plain. Correlative rocks east of the embayment typically form a series of four or more coarsening-upward fluvial cycles interbedded with thin limestone and dolomite. Coeval alluvial-fan and high-energy fluvial deposition occurred close to the highlands. We show the Peñasco uplift as a lowland at this time because some of the stream channels flowing out of the Uncompahgre–San Luis highlands appear to be deflected around the northern end of the uplift (unpublished data); there is no evidence, however, that the Peñasco uplift was a major source of clastics. Wind directions indicated by the Cedar Mesa Sandstone are inconsistent with the probable Wolfcampian paleolatitude of 0°–10° N. but most likely reflect the local influence of the Uncompahgre highlands (Parrish and Peterson, 1988).

Early De Chelly Time (Leonardian)

The lower part of the De Chelly Sandstone and the correlative Meseta Blanca Sandstone Member of the Yeso Formation represent the most extensive development of eolian dune deposits in the late Paleozoic San Juan trough (fig. 11*E*). Wind directions are generally consistent with the models discussed by Parrish and Peterson (1988) and indicate a paleolatitude about 10° N. During the time period illustrated in figure 11*E* coastal-sabkha and near-shore environments of the Yeso and Supai Formations were at their maximum extent.

SUMMARY

During the Pennsylvanian and Permian Periods the area of the present-day San Juan Basin was part of the Paradox Basin–San Juan trough, a northwest-trending basin bounded on the northeast by the Uncompahgre uplift of the Ancestral Rocky Mountains. The intracratonic deformation that produced these structures was most likely a result of continent-continent collisions taking place along the southern and southeastern margins of North America. Throughout this time the Paradox Basin–San Juan trough was within 10° of the paleoequator, and the climate was arid to semiarid. The Uncompahgre was a topographic high that strongly influenced wind directions and precipitation and was the principal source of clastic sediments.

At the close of the Mississippian the area was part of a vast karst plain developed on top of the Mississippian Leadville Limestone and equivalent rocks. The Uncompahgre, Pedernal, and Defiance-Zuni areas were probably slightly elevated, but the entire area had generally low relief. A residual soil developed on the karst surface and was subsequently reworked, partly by streams and partly by the advancing Pennsylvanian sea, to form the Molas and Log Springs Formations. As the sea continued to rise in the Atokan and early Desmoinesian, the area became a shallow carbonate shelf. Interbedded black shale was derived from the rising uplifts as were arkosic and quartzite debris (Uncompahgre and San Luis sources) in the northeastern part of the Pinkerton Trail Formation and quartzitic clastic sediments (San Luis highlands and

Pedernal source) in the correlative Sandia Formation to the southeast.

During the Desmoinesian, rates of uplift and subsidence increased dramatically. The Paradox Basin subsided more rapidly than the San Juan trough and was cut off from the sea a number of times, thus forming an evaporite basin in which shale-carbonate-evaporite cycles of the Paradox Formation were deposited. Deposits in the San Juan trough southeast of the Hogback fault contain similar cycles but lack the evaporites. Parts of the trough were probably exposed during low stands of the sea; however, many of the black shales deposited in the Paradox Basin during high stands are continuous into the San Juan trough, as are most of the carbonate rocks. The southeastern part of the area, although never exposed, did receive periodic floods of arkosic detritus from the rapidly rising Pedernal and Uncompahgre uplifts, resulting in the arkosic carbonate rocks of the Madera Limestone.

The Honaker Trail Formation and equivalent rocks in the Madera Limestone reflect a return to more normal shelf-type conditions throughout the area. In addition to deposition of carbonate rocks and shale, there was an increase in the grain size and in the amount of interbedded clastics in these rocks. These trends continued through deposition of the Late Pennsylvanian to Wolfcampian Rico Formation. The Rico and correlative Bursum Formation (recognized southeast of Albuquerque) represent the transition from Pennsylvanian, predominantly marine deposition to Permian continental redbed and arkose deposition. The age and lithology of the transition vary depending on location with respect to the highlands and to the trough axis, the transition being earlier near the highlands and later in the trough or near the sea.

The San Juan trough retained its general character during the Wolfcampian throughout deposition of the continental Cutler Group and equivalent rocks of the Supai and Abo Formations. The Defiance-Zuni uplift was active and contributed clastics from the south, as did the Uncompahgre uplift to the north and east and the Pedernal uplift to the southeast. A shift from dominantly northwest trending depositional axes in the Pennsylvanian to a mixture of northeast- and northwest-trending axes in the Permian probably reflects movement on basement blocks in response to a shifting stress field. The climate remained arid to semiarid, and most deposition was in eolian or fluvial environments.

The Halgaito and Organ Rock Formations are very similar. Away from the uplifts both are predominantly composed of loess, eolian sand-sheet, playa, and low-energy fluvial deposits. Near the uplifts, fan and high-energy fluvial deposits make up much of the interval. The intervening Cedar Mesa Sandstone reflects a period of renewed tectonism in the area that caused deposition of several cycles of high-energy fluvial deposits far out into the basin. Subsidence of the Four Corners platform block allowed marine encroachment from the south and development of a coastal sabkha between the Monument upwarp and the Hogback fault northward into Utah. Apparent deflection of Cedar Mesa streams southeastward around the Peñasco uplift provides additional evidence of tectonic activity in the area.

During the late Wolfcampian or early Leonardian, eolian dunes and sand sheets of the lower part of the De Chelly Sandstone and correlative Meseta Blanca Sandstone Member of the Yeso Formation covered most of the area. The Defiance-Zuni platform, just above sea level, was the site of a small coastal dune field. A coastal sabkha separated the erg from the sea to the south. The San Ysidro Member of the Yeso and the upper tongue of the Supai record cyclic advances and withdrawals of the Leonardian sea in the southern part of the area. The upper part of the De Chelly and correlative Glorieta Sandstone were deposited during another major advance of the dunes in the late Leonardian. The youngest preserved Permian sediments in the San Juan Basin area, the San Andres Limestone and correlative Bernal Formation, of late Leonardian to early Guadalupian age, record another major northward advance of the sea. Any additional Permian sediments were removed by Late Permian and Early Triassic erosion.

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Appendix—Geophysical Logs and Measured Outcrop Sections Used For This Study

Table A1. Number, location, operator, and well name of geophysical logs used for this study
[Grouped by State, County, township, range, and section. Holes not listed do not reach total depth in Permian or older rocks. Locations of wells shown by number on plate *1A*]

No.	Location	Operator and well name	County
		Utah	
1	Sec. 21, T. 38 S., R. 22 E.	Amoco Production Company, Ute Mountain Tribal No. 1	San Juan.
2	Sec. 15, T. 38 S., R. 23 E.	Halbert & Jennings, No. 1 L.N. Hagood-Federal	San Juan.
3	Sec. 10, T. 38 S., R. 24 E.	Mountain Fuel Supply Company, Cave Canyon No. 1	San Juan.
4	Sec. 19, T. 38 S., R. 24 E.	Skelly Oil Company, No. 1 R.J. Parks	San Juan.
5	Sec. 25, T. 38 S., R. 24 E.	McCulloch Oil Corp. of California, Federal No. 1–25	San Juan.
6	Sec. 15, T. 38 S., R. 25 E.	Mobil Oil Corp., Federal "HH"	San Juan.
7	Sec. 14, T. 39 S., R. 22 E.	Willard Pease, Cowboy No. 5	San Juan.
8	Sec. 15, T. 39 S., R. 23 E.	Continental Oil Company, Hatch Unit 15–1	San Juan.
9	Sec. 29, T. 39 S., R. 23 E.	Continental Oil Company, Bluff Unit No. 8	San Juan.
10	Sec. 32, T. 39 S., R. 23 E.	Shell Oil Company, No. 1 Bluff Unit	San Juan.
11	Sec. 4, T. 39 S., R. 24 E.	Reynolds Mining, No. 1 Hatch	San Juan.
12	Sec. 31, T. 39 S., R. 24 E.	The Carter Oil Company, No. 1 Govt.-Arrowhead	San Juan.
13	Sec. 5, T. 39 S., R. 25 E.	Hathaway Company, No. 1 Glasco-Federal	San Juan.
14	Sec. 22, T. 39 S., R. 25 E.	Zoller & Danneberg, No. 1 Navajo Canyon	San Juan.
15	Sec. 24, T. 39 S., R. 25 E.	Placid Oil Company, USA No. DU–5	San Juan.
16	Sec. 29, T. 39 S., R. 25 E.	Texaco, Inc., No. 1 Navajo AX	San Juan.
17	Sec. 15, T. 39 S., R. 26 E.	Mobil Oil Corp., No. 1 Federal GG	San Juan.
18	Sec. 5, T. 40 S., R. 22 E.	Zoller & Danneberg Exploration Ltd., Federal No. 1–5	San Juan.
19	Sec. 6, T. 40 S., R. 22 E.	Diamond Shamrock Corp., Turner Bluff No. 1–6	San Juan.
20	Sec. 17, T. 40 S., R. 22 E.	Midwest Oil Corp., Bluff Bench No. 1	San Juan.
21	Sec. 22, T. 40 S., R. 22 E.	Colorado Oil Company & Wolf Exploration Company, Bluff Bench No. 1	San Juan.
22	Sec. 9, T. 40 S., R. 23 E.	Black Dahlia Oil and Gas Company, Bass Navajo Federal No. 9–41	San Juan.
23	Sec. 10, T. 40 S., R. 23 E.	MacDonald Oil Corp., Humble-Federal No. 1	San Juan.
24	Sec. 20, T. 40 S., R. 23 E.	Zoller & Danneberg, Recapture Creek No. B–1	San Juan.
25	Sec. 26, T. 40 S., R. 23 E.	Davis Oil Company & Tiger Drilling Company, No. 1–F Federal	San Juan.
26	Sec. 31, T. 40 S., R. 23 E.	Norris Oil Company, Navajo No. 31–1	San Juan.
27	Sec. 34, T. 40 S., R. 23 E.	Norris Oil Company, Navajo No. 1–34	San Juan.
28	Sec. 3, T. 40 S., R. 24 E.	Standard Oil Company of California, No. 177–1 Navajo	San Juan.
29	Sec. 20, T. 40 S., R. 24 E.	Texaco, Inc., No. 30–D Navajo Tribe	San Juan.
30	Sec. 1, T. 40 S., R. 25 E.	Texaco, Inc., Navajo "H" No. 4	San Juan.
31	Sec. 4, T. 40 S., R. 25 E.	Zoller & Danneberg, NW Ismay No. 1	San Juan.
32	Sec. 5, T. 40 S., R. 25 E.	Mountain Fuel Supply Company, Cahone Mesa No. 5	San Juan.
33	Sec. 14, T. 40 S., R. 25 E.	Texas Pacific Oil Company, Navajo No. 1–14	San Juan.
34	Sec. 16, T. 40 S., R. 25 E.	Mountain Fuel Supply Company, No. 1 Cahone Mesa	San Juan.
35	Sec. 18, T. 40 S., R. 25 E.	W.O. Callaway, No. 1 Navajo	San Juan.
36	Sec. 9, T. 40 S., R. 26 E.	Shell Oil Company, No. 2 Hovenweep	San Juan.
37	Sec. 28, T. 40 S., R. 26 E.	Pure Oil Company, No. 28–B3 E. Aneth	San Juan.
38	Sec. 31, T. 40 S., R. 26 E.	Monsanto Company, Navajo A–4	San Juan.
39	Sec. 13, T. 41 S., R. 22 E.	Carter Oil Company, No. 50–1 Navajo	San Juan.
40	Sec. 35, T. 41 S., R. 22 E.	Davis Oil Company, No. 1 Anadarko	San Juan.
41	Sec. 23, T. 41 S., R. 23 E.	Aztec Oil & Gas Company, Navajo 78–1	San Juan.
42	Sec. 1, T. 41 S., R. 24 E.	Carter Oil Company, No. 1–13 Navajo	San Juan.
43	Sec. 22, T. 41 S., R. 24 E.	Phillips Petroleum–Aztec Oil & Gas Company, No. 3–A Navajo	San Juan.
44	Sec. 15, T. 41 S., R. 25 E.	Bridger Petroleum, Inc., Navajo Bridger–Continental 1–15	San Juan.
45	Sec. 8, T. 41 S., R. 26 E.	Kimbark Exploration Company & Zoller & Danneberg, Mail Trail Mesa No. 1	San Juan.
46	Sec. 28, T. 41 S., R. 26 E.	Superior Oil Company, No. 1–28 Navajo	San Juan.
47	Sec. 22, T. 42 S., R. 22 E.	Pacific Natural Gas Exploration Company, North Boundary Butte No. 41–22	San Juan.
48	Sec. 2, T. 42 S., R. 23 E.	Shell Oil Company, Desert Creek No. 1	San Juan.
49	Sec. 27, T. 42 S., R. 23 E.	Gulf Oil Company, No. 1 White Mesa	San Juan.
50	Sec. 15, T. 42 S., R. 24 E.	Davis Oil Company, Superior-Navajo No. 1	San Juan.
51	Sec. 22, T. 42 S., R. 24 E.	Carter Oil Company, No. 2 Navajo White Mesa	San Juan.
52	Sec. 12, T. 42 S., R. 25 E.	Humble Oil & Refining Company, No. 1 Navajo–136	San Juan.
53	Sec. 10, T. 42 S., R. 26 E.	R.G. Boekel, Navajo No. 32–10	San Juan.
54	Sec. 28, T. 42 S., R. 26 E.	Tiger Oil Company & Davis Oil Company, Navajo No. 1	San Juan.
55	Sec. 22, T. 43 S., R. 22 E.	Western Natural Gas Company, No. 1 P.B. English	San Juan.

Table A1. Number, location, operator, and well name of geophysical logs used for this study

No.	Location	Operator and well name	County
		Utah—Continued	
56	Sec. 4, T. 43 S., R. 23 E.	Sunray DX Oil –Navajo B–1	San Juan.
57	Sec. 11, T. 43 S., R. 24 E.	Amerada Petroleum, No. 1 Carter–Navajo–110	San Juan.
58	Sec. 16, T. 43 S., R. 25 E.	Superior Oil Company, No. 12–16 Navajo–N	San Juan.
59	Sec. 19, T. 43 S., R. 26 E.	Davis Oil Company & Tiger Drilling Company, No. 1–E Navajo	San Juan.
60	Sec. 31, T. 43 S., R. 26 E.	The Carter Oil Company, No. 1 Navajo–Four Corners	San Juan.
		Colorado	
61	Sec. 15, T. 37 N., R. 20 W.	Big Horn Powder River, No. 1–A Govt.	Montezuma.
62	Sec. 24, T. 37 N., R. 20 W.	Texota Oil–Ambassador Oil, No. 1–B Colorado-Federal	Montezuma.
63	Sec. 6, T. 37 N., R. 19 W.	Mobil Oil Corp., No. 1 Federal–II	Montezuma.
64	Sec. 21, T. 37 N., R. 19 W.	Pan American Petroleum Corp., No. 1 Fehr	Montezuma.
65	Sec. 8, T. 37 N., R. 18 W.	Calvert Drilling Inc., No. 1 Woods Canyon	Montezuma.
66	Sec. 36, T. 37 N., R. 18 W.	Shell Oil Company, Federal 36–37–18 No. 1	Montezuma.
67	Sec. 5, T. 37 N., R. 17 W.	Harbor Oil & Gas–J.R. Brown, No. 1 Reed	Montezuma.
68	Sec. 27, T. 37 N., R. 17 W.	Gulf Oil Company, No. 1 Fulks	Montezuma.
69	Sec. 4, T. 37 N., R. 16 W.	Shell Oil Company, State 4–37–16 No. 1	Montezuma.
70	Sec. 34, T. 37 N., R. 16 W.	Fundamental Oil Company, Elliot No. 1–34	Montezuma.
71	Sec. 2, T. 37 N., R. 15 W.	Read and Stevens, Inc., Shenandoah–Veach No. 1	Montezuma.
72	Sec. 34, T. 37 N., R. 14 W.	Davis Oil Company, Bayles No. 1	Montezuma.
73	Sec. 1, T. 36 N., R. 19 W.	Pan American Petroleum Corp., USA Pan Am "B" No. 1	Montezuma.
74	Sec. 9, T. 36 N., R. 18 W.	Shell Oil Company, Federal 9–36–18 No. 1	Montezuma.
75	Sec. 20, T. 36 N., R. 18 W.	Great Western Drilling Company, No. 1 W. McElmo-Govt.	Montezuma.
76	Sec. 25, T. 36 N., R. 18 W.	Byrd-Frost, No. 1 MacIntosh	Montezuma.
77	Sec. 23, T. 36 N., R. 17 W.	Shell Oil Company, Federal 23–36–17 No. 1	Montezuma.
78	Sec. 18, T. 36 N., R. 14 W.	Reynolds Mining, No. 1 Point Lookout	Montezuma.
79	Sec. 8, T. 36 N., R. 13 W.	Walter Duncan, Culp No. 1	Montezuma.
80	Sec. 11, T. 36 N., R. 13 W.	Arapahoe Drilling Company, Arapahoe Reddert No. 1	Montezuma.
81	Sec. 3, T. 35 N., R. 20 W.	Tom Vessels Jr., Vessels No. 1	Montezuma.
82	Sec. 14, T. 35 N., R. 20 W.	Kimbark Exploration Company & Alpine Oil Company, Govt. Flodine No. 1	Montezuma.
83	Sec. 25, T. 35 N., R. 20 W.	Monsanto Company, Duncan No. 1	Montezuma.
85	Sec. 33, T. 35 N., R. 19 W.	The Texas Company, No. 1–A Jones-Federal	Montezuma.
86	Sec. 1, T. 35 N., R. 17 W.	George M. Hill National Drilling Company, No. 1 McCabe	Montezuma.
87	Sec. 1, T. 35 N., R. 14 W.	Slick-Moorman Oil Company, No. 1 C.J. Weber	Montezuma.
88	Sec. 3, T. 35 N., R. 13 W.	Davis Oil Company, Elliott Federal No. 1	Montezuma.
89	Sec. 1, T. 34 N., R. 20 W.	Pan American Petroleum Corp., Ute Mountain Tribal "J" No. 2	Montezuma.
90	Sec. 11, T. 34 N., R. 20 W.	Phillips Petroleum Company, No. 2 Desert Canyon	Montezuma.
91	Sec. 12, T. 34 N., R. 20 W.	Vaughey & Vaughey, No. 1–A Ute	Montezuma.
92	Sec. 6, T. 34 N., R. 19 W.	Atlantic Richfield Company, West Ute Mountain No. 1	Montezuma.
93	Sec. 1, T. 34 N., R. 17 W.	National Drilling Company, Higgins No. 1	Montezuma.
94	Sec. 24, T. 34 N., R. 14 W.	Houston Oil & Minerals Corp., Ute Mountain Federal No. 14–24	Montezuma.
95	Sec. 34, T. 34 N., R. 14 W.	Houston Oil and Minerals Corp., Ute Mountain No. 44–34	Montezuma.
96	Sec. 3, T. 33½ N., R. 20 W.	The California Company, No. 5 Calco Superior Ute	Montezuma.
97	Sec. 11, T. 33½ N., R. 20 W.	Walter Duncan, Calco Superior Ute No. 1	Montezuma.
98	Sec. 14, T. 33½ N., R. 20 W.	Walter Duncan, Ute No. 1–14	Montezuma.
99	Sec. 15, T. 33½ N., R. 20 W.	Chevron Oil Company, Chevron Ute Tribal No. 9 (11–15)	Montezuma.
100	Sec. 34, T. 33½ N., R. 20 W.	Pure Oil Company, No. 1 Ute Tribal	Montezuma.
101	Sec. 4, T. 33 N., R. 20 W.	Forest Oil Corp., Ute 4–1	Montezuma.
102	Sec. 13, T. 33 N., R. 20 W.	Rocket Drilling Company, No. 1–D Ute	Montezuma.
103	Sec. 15, T. 33 N., R. 20 W.	Continental Oil Company, No. 3	Montezuma.
104	Sec. 23, T. 33 N., R. 20 W.	Signal Exploration Inc.-et al., Marianna Springs–Ute Gov't. No. 1	Montezuma.
105	Sec. 17, T. 33 N., R. 19 W.	Texaco, Inc., Ute Mountain Tribal B No. 1	Montezuma.
106	Sec. 22, T. 33 N., R. 19 W.	The California Company, No. 1 Ute Tribal	Montezuma.
107	Sec. 22, T. 33 N., R. 18 W.	The California Company, Ute Mountain Tribal No. 1	Montezuma.
108	Sec. 23, T. 33 N., R. 18 W.	Wintershall Oil & Gas Corp., Ute Mountain Tribal 23–32 Nighthawk	Montezuma.
109	Sec. 9, T. 33 N., R. 17 W.	King Resources Company, Ute No. 1	Montezuma.
110	Sec. 8, T. 33 N., R. 14 W.	Tidewater Associated Oil Company, No. 1 Ute	Montezuma.
111	Sec. 2, T. 32 N., R. 20 W.	Continental Oil Company, No. 4 Govt.	Montezuma.
112	Sec. 17, T. 32 N., R. 20 W.	Honolulu Oil Company, No. 1 Govt.	Montezuma.
113	Sec. 24, T. 32 N., R. 20 W.	Pan American Petroleum Corp., No. 1 Ute Mountain	Montezuma.
114	Sec. 7, T. 32 N., R. 19 W.	Continental Oil, Ute Mountain No. 1	Montezuma.
115	Sec. 19, T. 32 N., R. 19 W.	Continental Oil Company, No. 5 Ute Indian	Montezuma.

Table A1. Number, location, operator, and well name of geophysical logs used for this study

No.	Location	Operator and well name	County
		Colorado—Continued	
116	Sec. 23, T. 32 N., R. 19 W.	Rocket Drilling–Mohawk Petroleum, No. 1–C Ute	Montezuma.
118	Sec. 1, T. 32 N., R. 17 W.	Phillips-Mobil, Mesa "A" No. 1	Montezuma.
119	Sec. 21, T. 32 N., R. 15 W.	Amerada Petroleum Corp., Ute Tribal No. 2	Montezuma.
120	Sec. 32, T. 36 N., R. 12 W.	Davis Oil Company, Peaker Federal No. 1	La Plata.
121	Sec. 17, T. 35 N., R. 12 W.	Miller & Shelly, Karl Hauert No. 1	La Plata.
122	Sec. 26, T. 35 N., R. 10 W.	Cayman Corp., Colorado Federal No. 1	La Plata.
123	Sec. 3, T. 34 N., R. 13 W.	Davis Oil Company, Menefee Federal No. 1	La Plata.
124	Sec. 15, T. 34 N., R. 13 W.	Cities Service Oil Company, Story A No. 1	La Plata.
125	Sec. 28, T. 34 N., R. 12 W.	General Petroleum Corp., No. 44–28 Butler	La Plata.
126	Sec. 3, T. 34 N., R. 11 W.	Great Western Drilling Company, Ft. Lewis School Land No. 1	La Plata.
127	Sec. 11, T. 34 N., R. 11 W.	Texaco Inc., State "O" No. 1	La Plata.
128	Sec. 17, T. 34 N., R. 11 W.	General Petroleum Corp., No. 55–17 Kikel	La Plata.
130	Sec. 24, T. 33 N., R. 14 W.	Norris Oil Company, Ute No. 1	La Plata.
131	Sec. 15, T. 33 N., R. 13 W.	Skelly Oil Company, No. 1 L.F. Benton	La Plata.
132	Sec. 14, T. 33 N., R. 12 W.	The Hathaway Company, No. 1 Barr	La Plata.
133	Sec. 23, T. 33 N., R. 12 W.	Davis Oil Company, Red Mesa Deep No. 1	La Plata.
135	Sec. 17, T. 33 N., R. 7 W.	Stanolind Oil & Gas, No. 6–B Ute Indian	La Plata.
136	Sec. 9, T. 32 N., R. 14 W.	El Paso Natural Gas Company, No. 9 Ute	La Plata.
137	Sec. 4, T. 32 N., R. 13½ W.	Knight and Miller Oil Corp., Aztec-Ute No. 1	La Plata.
139	Sec. 5, T. 33 N., R. 2 W.	The Daube Company, Florance Newton No. 1	Archuleta.
141	Sec. 24, T. 33 N., R. 2 E.	William E. Hughes, Gramps No. 51	Archuleta.
143	Sec. 2, T. 32 N., R. 3 E.	Wm. E. Hughes, J. Miller No. 1	Archuleta.
		Arizona	
144	Sec. 29, T. 41 N., R. 27 E.	Hancock Oil Company, No. 1–29 Dinne Tribal	Apache.
145	Sec. 4, T. 41 N., R. 29 E.	Champlin-Moncrief, Navajo 135 No. 1	Apache.
146	Sec. 22, T. 41 N., R. 29 E.	E. B. LaRue, Toh Ahtin No. 1	Apache.
147	Sec. 29, T. 41 N., R. 29 E.	Davis Oil Company & Tiger Drilling Company, No. 1–C Navajo	Apache.
148	Sec. 16, T. 41 N., R. 30 E.	Superior Oil Company, No. 2–H Navajo	Apache.
149	Sec. 21, T. 41 N., R. 30 E.	Superior Oil Company, No. 23–21–M Navajo	Apache.
150	Sec. 30, T. 41 N., R. 30 E.	Miami Oil Producers, Inc., Miami Navajo 41–54 No. 1	Apache.
151	Sec. 36, T. 41 N., R. 30 E.	Texaco, Inc., No. 1–Z Navajo	Apache.
152	Sec. 7, T. 41 N., R. 31 E.	Zoller & Danneberg, Navajo 161–1	Apache.
153	Sec. 6, T. 40 N., R. 27 E.	Occidental Petroleum Corp., Texaco-Navajo No. 1	Apache.
154	Sec. 9, T. 40 N., R. 28 E.	Curtis Little–Aircoil, West Dry Mesa No. 1	Apache.
155	Sec. 17, T. 40 N., R. 28 E.	Western States Petroleum Company, No. 2 Navajo	Apache.
156	Sec. 15, T. 40 N., R. 29 E.	Pan American Petroleum Corp., Moko Navajo No. 1	Apache.
157	Sec. 21, T. 40 N., R. 29 E.	Cities Service Oil Company, Monsanto Navajo No. 1	Apache.
158	Sec. 27, T. 40 N., R. 29 E.	Cities Service Oil Company, Monsanto Navajo "B" No. 1	Apache.
159	Sec. 2, T. 40 N., R. 30 E.	Depco, Inc., Midwest & Occidental, Navajo No. 1–2	Apache.
160	Sec. 5, T. 40 N., R. 30 E.	British-American Oil Producing Company, Navajo "C" 1	Apache.
161	Sec. 20, T. 38 N., R. 27 E.	Pan American Petroleum Corp., Navajo Tribal T No. 1	Apache.
162	Sec. 16, T. 38 N., R. 29 E.	Pan American Petroleum Corp., Navajo Tribal No. V–1	Apache.
163	Sec. 2, T. 38 N., R. 30 E.	Depco, Inc., Navajo Tribal 4–2	Apache.
164	Sec. 12, T. 38 N., R. 30 E.	Pan American Petroleum Corp., Navajo Tribal AF No. 1	Apache.
165	Sec. 18, T. 38 N., R. 30 E.	Skelly Oil Company, Navajo Q–1	Apache.
166	Sec. 32, T. 38 N., R. 30 E.	Pure-Sun-Tidewater Oil Companies, Navajo 103 No. 1	Apache.
167	Sec. 8, T. 37 N., R. 27 E.	Vaughey, Vaughey & Blackburn, Navajo No. 8–1	Apache.
168	Sec. 24, T. 37 N., R. 28 E.	Buttes Gas & Oil Company, Navajo 1–24	Apache.
169	Sec. 32, T. 37 N., R. 28 E.	Curtis Little, Pete's Nose No. 1	Apache.
170	Sec. 12, T. 37 N., R. 29 E.	Gulf Oil Corp., USA Navajo "BS" No. 1	Apache.
171	Sec. 22, T. 37 N., R. 29 E.	Curtis J. Little, Tsegehot-Tsane 1–22	Apache.
172	Sec. 33, T. 37 N., R. 29 E.	Odessa Natural Gas Company, Aircodessa Cove No. 1	Apache.
173	Sec. 35, T. 37 N., R. 29 E.	Vaughey, Vaughey & Blackburn, Navajo No. 35–1	Apache.
174	Sec. 34, T. 37 N., R. 30 E.	Gulf Oil Company, U.S., Navajo CS No. 1	Apache.
175	Sec. 30, T. 36 N., R. 27 E.	M.A. Riddle & J. Gottlieb, Navajo No. 1	Apache.
176	Sec. 6, T. 36 N., R. 28 E.	Vaughey & Vaughey & Blackburn, Navajo No. 6–1	Apache.
177	Sec. 4, T. 36 N., R. 29 E.	Union Oil Company of California, Navajo 3741 Lukachukai No. 1P4	Apache.
178	Sec. 17, T. 36 N., R. 29 E.	Union Oil Company of Californian, No. 1–M17 Giant	Apache.
179	Sec. 6, T. 36 N., R. 30 E.	Union Texas Petroleum, Navajo No. 1–6	Apache.
180	Sec. 20, T. 36 N., R. 30 E.	Kerr-McGee Corp., Navajo "E" No. 1	Apache.

Table A1. Number, location, operator, and well name of geophysical logs used for this study

No.	Location	Operator and well name	County
		Arizona—Continued	
181	Sec. 29, T. 36 N., R. 30 E.	Kerr-McGee Corp., Navajo No. 8	Apache.
182	Sec. 31, T. 36 N., R. 30 E.	Kerr-McGee Corp., Navajo No. 5	Apache.
183	Sec. 32, T. 36 N., R. 30 E.	Kerr-McGee Corp., No. 1 Navajo	Apache.
184	Sec. 5, T. 35 N., R. 28 E.	Buttes Gas & Oil Company, Navajo No. 1	Apache.
185	Sec. 25, T. 35 N., R. 28 E.	Buttes Gas & Oil Company, No. 1–25 Navajo	Apache.
186	Sec. 25, T. 35 N., R. 29 E.	Curtis Little & E.R. Richardson, Tohotso No. 1	Apache.
187	Sec. 3, T. 35 N., R. 30 E.	Anadarko Production Company, Navajo 1–135	Apache.
188	Sec. 6, T. 35 N., R. 30 E.	Humble Oil and Refining Company, Navajo tract 138 No. 2	Apache.
189	Sec. 10, T. 35 N., R. 30 E.	Odessa Natural Gas Company, Aircodessa-Se Dineh-Bi-Keyah No. 1	Apache.
190	Sec. 14, T. 35 N., R. 30 E.	Kerr-McGee Corp., Navajo No. H–1	Apache.
191	Sec. 35, T. 35 N., R. 30 E.	Humble Oil & Refining Company, No. 1 Navajo 151	Apache.
192	Sec. 4, T. 34 N., R. 28 E.	Gulf Oil Corp., Navajo 4 No. 1	Apache.
193	Sec. 11, T. 7 N., R. 8 W.	Gulf Oil Corp., Navajo 11–1	Apache.
194	Sec. 22, T. 7 N., R. 8 W.	Gulf Oil Corp., Navajo 22, Well No. 1	Apache.
195	Sec. 7, T. 7 N., R. 7 W.	Depco-Husky-Midwest, No. 1 Navajo Tribal	Apache.
196	Sec. 15, T. 7 N., R. 7 W.	Ed Doherty, Navajo No. 1–15	Apache.
197	Sec. 26, T. 7 N., R. 7 W.	Texaco, Inc., Texaco-Navajo No. 1–BC	Apache.
198	Sec. 32, T. 7 N., R. 7 W.	Pan American Petroleum Corp., Navajo Tribal AB No. 1	Apache.
199	Sec. 26, T. 6 N., R. 8 W.	Curtis J. Little, Bear Springs No. 1	Apache.
200	Sec. 12, T. 6 N., R. 7 W.	Gulf Oil Company, Navajo Defiance No. 1	Apache.
201	Sec. 26, T. 6 N., R. 7 W.	Texaco, Inc., Navajo B–F No. 1	Apache.
202	Sec. 20, T. 6 N., R. 6 W.	Union Oil Company, Navajo 1–166	Apache.
203	Sec. 11, T. 4 N., R. 7 W.	Gulf Oil Company, USA, Navajo Texaco No. 1	Apache.
204	Sec. 36, T. 4 N., R. 7 W.	Gulf Oil Company, Navajo "BW" No. 1	Apache.
		New Mexico	
205	Sec. 26, T. 32 N., R. 21 W.	El Paso Natural Gas, No. 2 Bita Peak	San Juan.
206	Sec. 13, T. 32 N., R. 20 W.	Continental Oil Company, Navajo Tribal No. 1–13	San Juan.
207	Sec. 26, T. 32 N., R. 20 W.	Continental Oil Company, No. 1 Ute Mtn.	San Juan.
208	Sec. 30, T. 32 N., R. 20 W.	Humble Oil & Continental Oil, No. 3–B Navajo	San Juan.
209	Sec. 36, T. 32 N., R. 20 W.	Tenneco Oil Company, Navajo 590 No. 1	San Juan.
210	Sec. 21, T. 32 N., R. 19 W.	Continental Oil Company, No. 1–21 Navajo	San Juan.
211	Sec. 33, T. 32 N., R. 19 W.	Compass Exploration, Inc., Indian 1–33	San Juan.
212	Sec. 17, T. 32 N., R. 18 W.	The Texas Company, No. 1–N Navajo	San Juan.
213	Sec. 32, T. 32 N., R. 18 W.	Compass Exploration, Inc., 1–32 Navajo	San Juan.
214	Sec. 35, T. 32 N., R. 18 W.	Texaco, Inc., Navajo AJ No. 1	San Juan.
215	Sec. 36, T. 32 N., R. 18 W.	Southern Union Gas Company, Navajo No. 1A	San Juan.
216	Sec. 28, T. 32 N., R. 17 W.	Texas Pacific Coal & Oil Company, No. 1–B Navajo	San Juan.
217	Sec. 25, T. 32 N., R. 16 W.	Cities Service Oil Company, Ute A No. 1	San Juan.
218	Sec. 31, T. 32 N., R. 15 W.	Forest Oil Company–Kern County Land, et al., No. 1 Ute	San Juan.
219	Sec. 10, T. 32 N., R. 14 W.	El Paso-Delhi Oil Corp., No. 4 Delhi	San Juan.
220	Sec. 15, T. 32 N., R. 14 W.	El Paso Natural Gas Company, Ute No. 8	San Juan.
221	Sec. 19, T. 32 N., R. 14 W.	El Paso Natural Gas Company, No. 7 Ute	San Juan.
222	Sec. 21, T. 32 N., R. 14 W.	Southern Union Production Company, Barker No. 19	San Juan.
223	Sec. 25, T. 32 N., R. 14 W.	Amoco Production Company, Mountain Ute Gas Com "F" No. 1	San Juan.
224	Sec. 29, T. 32 N., R. 14 W.	Aztec Oil & Gas Company, No. 13 Barker Dome	San Juan.
225	Sec. 33, T. 32 N., R. 14 W.	Pan American Petroleum Corp., Ute Mountain Tribal No. K–1	San Juan.
226	Sec. 36, T. 32 N., R. 14 W.	Stanolind Oil & Gas, No. 4 Ute Indian	San Juan.
230	Sec. 15, T. 31 N., R. 20 W.	British-American Oil Prod. Company, No. 1–E Navajo	San Juan.
231	Sec. 19, T. 31 N., R. 20 W.	Atlantic Richfield Company, No. 1 Chevron-Ladd	San Juan.
232	Sec. 7, T. 31 N., R. 19 W.	Monsanto Chemical Company, Natoni No. 1	San Juan.
233	Sec. 10, T. 31 N., R. 19 W.	Pan American Petroleum Corp., No. 1–B Navajo	San Juan.
234	Sec. 17, T. 31 N., R. 19 W.	The Superior Company, Navajo X No. 1	San Juan.
235	Sec. 4, T. 31 N., R. 18 W.	Humble Oil & Refining Company, No. 1–H Navajo	San Juan.
236	Sec. 8, T. 31 N., R. 18 W.	Humble Oil & Refining, No. 1–C Navajo	San Juan.
237	Sec. 15, T. 31 N., R. 18 W.	Humble Oil & Refining Company, Navajo Tract 24 No. 1	San Juan.
238	Sec. 22, T. 31 N., R. 18 W.	Standard Oil Company of Texas, Navajo Tribal 24 No. 22–1	San Juan.
239	Sec. 29, T. 31 N., R. 18 W.	Cactus Drilling Corp., Cactus Navajo "A" No. 1	San Juan.
240	Sec. 35, T. 31 N., R. 18 W.	Standard Oil Company of Texas, Navajo Tribal No. 1–21	San Juan.
241	Sec. 6, T. 31 N., R. 17 W.	Honolulu Oil Corp., Navajo No. 1	San Juan.
242	Sec. 22, T. 31 N., R. 17 W.	Reynolds Mining Corp., No. 1 Navajo-Lease 7652	San Juan.

Table A1. Number, location, operator, and well name of geophysical logs used for this study

No.	Location	Operator and well name	County
		New Mexico—Continued	
243	Sec. 27, T. 31 N., R. 17 W.	Three States Natural Gas Company, Navajo No. 1	San Juan.
244	Sec. 34, T. 31 N., R. 17 W.	The Texas Company, No. 3–A Navajo	San Juan.
245	Sec. 3, T. 31 N., R. 16 W.	Standard Oil Company of Texas, No. 1–6 Navajo Ute	San Juan.
246	Sec. 2, T. 31 N., R. 14 W.	Stanolind Oil & Gas Company, No. 7 Ute Indian	San Juan.
247	Sec. 10, T. 31 N., R. 14 W.	Pan American Petroleum Corp., No. 1–D Ute Mtn Tribal	San Juan.
248	Sec. 15, T. 31 N., R. 14 W.	Riddle & Gottlieb, Ute Mountain Tribal No. 1	San Juan.
249	Sec. 13, T. 30 N., R. 21 W.	Pan American Oil Corp., Navajo Tribal "AD" No. 1	San Juan.
250	Sec. 5, T. 30 N., R. 20 W.	John H. Hill, Atlantic Navajo No. 1	San Juan.
251	Sec. 23, T. 30 N., R. 20 W.	Pure Oil Company & Ohio Oil Company, No. 1–11 Navajo	San Juan.
252	Sec. 24, T. 30 N., R. 20 W.	Amerada Petroleum Corp., No. 1 Navajo-Tract 10	San Juan.
253	Sec. 12, T. 30 N., R. 19 W.	Sinclair Oil & Gas Company, Navajo Tribal 4000–San Juan No. 1	San Juan.
254	Sec. 8, T. 30 N., R. 18 W.	Texaco, Inc., Navajo Tribal AP–IX	San Juan.
255	Sec. 11, T. 30 N., R. 18 W.	Standard Oil Company of Texas, Navajo Tribal 22 No. 11–1	San Juan.
256	Sec. 14, T. 30 N., R. 18 W.	Cactus Drilling Corp., Navajo B No. 1	San Juan.
257	Sec. 5, T. 30 N., R. 17 W.	Phillips Petroleum, Navajo No. 1	San Juan.
258	Sec. 15, T. 30 N., R. 17 W.	Standard Oil Company of Texas, Navajo Tribal 130 No. 15–1	San Juan.
259	Sec. 23, T. 30 N., R. 16 W.	Stanolind Oil & Gas Company, No. 1 O.J. Hoover	San Juan.
260	Sec. 31, T. 30 N., R. 16 W.	Humble Oil & Refining Company, No. 2–K Navajo	San Juan.
261	Sec. 11, T. 30 N., R. 14 W.	Humble Oil & Refining Company, North Kirtland Unit No. 1	San Juan.
262	Sec. 28, T. 30 N., R. 14 W.	Mountain Fuel Supply Company, Fruitland No. 1	San Juan.
265	Sec. 2, T. 29 N., R. 19 W.	Continental Oil Company, Rattlesnake No. 136	San Juan.
266	Sec. 12, T. 29 N., R. 19 W.	Continental Oil Company, Rattlesnake No. 142	San Juan.
267	Sec. 13, T. 29 N., R. 19 W.	Continental Oil Company, Rattlesnake No. 147	San Juan.
268	Sec. 19, T. 29 N., R. 18 W.	Continental Oil Company, Kern County Rattlesnake No. 1	San Juan.
269	Sec. 21, T. 29 N., R. 18 W.	Kern County Land Company, No. 1–21 Shell-Navajo	San Juan.
270	Sec. 1, T. 29 N., R. 17 W.	Pan American Petroleum Corp., No. 1–C Navajo	San Juan.
271	Sec. 11, T. 29 N., R. 17 W.	San Juan Drilling Company, No. 1 Navajo–Fred Hamrah	San Juan.
272	Sec. 12, T. 29 N., R. 17 W.	Stanolind Oil & Gas Company, No. 1 Navajo	San Juan.
273	Sec. 20, T. 29 N., R. 17 W.	Zoller & Danneburg, Pajarito Navajo No. 1	San Juan.
274	Sec. 25, T. 29 N., R. 17 W.	M.M. Garrett, No. 1 Navajo	San Juan.
275	Sec. 30, T. 29 N., R. 17 W.	Amerada Petroleum Corp., Navajo Tract 20 No. 2	San Juan.
276	Sec. 31, T. 29 N., R. 17 W.	Amerada Petroleum Corp., Navajo No. 1	San Juan.
277	Sec. 19, T. 29 N., R. 16 W.	Stanolind Oil & Gas Company, U.S.G. No. 13	San Juan.
278	Sec. 18, T. 29 N., R. 15 W.	Pure, Sun, Humble, 1–2 Navajo	San Juan.
280	Sec. 27, T. 28 N., R. 19 W.	Amerada Petroleum Corp., Navajo No. 1–32	San Juan.
281	Sec. 13, T. 28 N., R. 18 W.	Champlin Petroleum Company, Navajo 1–12	San Juan.
282	Sec. 27, T. 28 N., R. 17 W.	Sunray DX, Navajo Table Mesa No. 1	San Juan.
283	Sec. 33, T. 28 N., R. 17 W.	Continental Oil Company, Table Mesa No. 28	San Juan.
286	Sec. 7, T. 27 N., R. 20 W.	Texaco, Inc., Navajo AW No. 1	San Juan.
287	Sec. 21, T. 27 N., R. 19 W.	Northwest Pipeline Corp., Barbara Kay No. 2	San Juan.
288	Sec. 28, T. 27 N., R. 19 W.	Texaco, Inc., Navajo AS No. 1	San Juan.
289	Sec. 34, T. 27 N., R. 18 W.	Sinclair Oil & Gas Company, Navajo Tribal 141 No. 1	San Juan.
290	Sec. 3, T. 27 N., R. 17 W.	Continental Oil Company, No. 3–18 Table Mesa	San Juan.
291	Sec. 4, T. 27 N., R. 17 W.	Continental Oil Company, No. 24 Table Mesa	San Juan.
292	Sec. 9, T. 27 N., R. 17 W.	Continental Oil Company, Table Mesa No. 29	San Juan.
293	Sec. 20, T. 27 N., R. 17 W.	Amerada Petroleum Corp., Navajo tract 4 No. 1	San Juan.
294	Sec. 19, T. 27 N., R. 16 W.	Continental Oil Company, Chaco Wash Navajo No. 1	San Juan.
295	Sec. 25, T. 26 N., R. 20 W.	Gulf Oil Company, USA, Navajo "BB: No. 1	San Juan.
296	Sec. 5, T. 26 N., R. 19 W.	Amerada Petroleum Corp., Navajo Tract 381 No. 1	San Juan.
297	Sec. 21, T. 26 N., R. 19 W.	Apache Corp., Navajo Tribal Tract 52 No. 1–21	San Juan.
298	Sec. 30, T. 26 N., R. 19 W.	Humble Oil & Refining Company, No. 1–D Navajo	San Juan.
299	Sec. 8, T. 26 N., R. 18 W.	Pan American Petroleum Corp., Navajo Tribal 'P' No. 3	San Juan.
300	Sec. 10, T. 26 N., R. 18 W.	Curtis J. Little, Navajo Tocito No. 3	San Juan.
301	Sec. 16, T. 26 N., R. 18 W.	Pan American Petroleum Corp., Navajo Tribal "U" No. 3	San Juan.
302	Sec. 17, T. 26 N., R. 18 W.	Stanolind Oil & Gas Co. and Continental Oil Co. Tocito Unit No. 1	San Juan.
303	Sec. 18, T. 26 N., R. 18 W.	Pan American Petroleum Corp., Navajo Tribal N No. 4	San Juan.
304	Sec. 21, T. 26 N., R. 18 W.	Pan American Petroleum Corp., Navajo Tribal U No. 4	San Juan.
305	Sec. 23, T. 26 N., R. 18 W.	Sinclair Oil & Gas Company, Navajo 149–San Juan Well No. 1	San Juan.
306	Sec. 27, T. 26 N., R. 18 W.	Texaco, Inc., Navajo Tribe AR No. 8	San Juan.
307	Sec. 28, T. 26 N., R. 18 W.	Texaco, Inc., Navajo AL No. 1	San Juan.

Table A1. Number, location, operator, and well name of geophysical logs used for this study

No.	Location	Operator and well name	County
		New Mexico—Continued	
308	Sec. 32, T. 26 N., R. 15 W.	Pure Oil Company, No. 1–27 Navajo	San Juan.
309	Sec. 34, T. 26 N., R. 14 W.	Skelly Oil Company, Navajo "O" No. 1	San Juan.
312	Sec. 12, T. 26 N., R. 10 W.	El Paso Natural Gas Company, Huerfano 265	San Juan.
316	Sec. 16, T. 25 N., R. 19 W.	Champlin Petroleum Company, Navajo Humble No. 1	San Juan.
317	Sec. 33, T. 25 N., R. 19 W.	Texaco, Inc., Navajo Tribe "AO" No. 1	San Juan.
318	Sec. 4, T. 25 N., R. 16 W.	Pan American Petroleum Corp., No. 1 Gulf Navajo	San Juan.
319	Sec. 28, T. 25 N., R. 16 W.	Gulf Oil Corp., No. 1 Navajo	San Juan.
320	Sec. 17, T. 25 N., R. 11 W.	Shell Oil Company, No. 113–17 Carson Unit	San Juan.
321	Sec. 20, T. 24 N., R. 20 W.	Kerr-McGee Corp., Navajo K–1	San Juan.
322	Sec. 28, T. 24 N., R. 20 W.	Kerr-McGee Corp., Kerr-McGee Navajo L1	San Juan.
323	Sec. 34, T. 24 N., R. 20 W.	Kerr-McGee Corp., Navajo I–1	San Juan.
324	Sec. 14, T. 24 N., R. 17 W.	Amoco Production Company, Navajo Tribal "AA" No. 1	San Juan.
325	Sec. 9, T. 23 N., R. 20 W.	Kerr-McGee Corp., Navajo M No. 1	San Juan.
326	Sec. 12, T. 23 N., R. 20 W.	Kerr-McGee Corp., Navajo A No. 1	San Juan.
327	Sec. 23, T. 23 N., R. 20 W.	Kerr-McGee Corp., Navajo No. J–1	San Juan.
328	Sec. 22, T. 23 N., R. 14 W.	Woods Petroleum Corp., Navajo No. 1–22	San Juan.
329	Sec. 9, T. 23 N., R. 13 W.	Apache Corp., Foshay No. 1	San Juan.
331	Sec. 12, T. 23 N., R. 9 W.	Sun Oil Company, AH DES P I AH Navajo No. 1	San Juan.
335	Sec. 10, T. 22 N., R. 14 W.	H.A. Chapman, Navajo No. 1–10	San Juan.
337	Sec. 25, T. 22 N., R. 9 W.	Sun Oil Company et al, Navajo lands No. 1	San Juan.
339	Sec. 1, T. 21 N., R. 14 W.	Southern Union Production Company, Navajo No. 1	San Juan.
344	Sec. 23, T. 32 N., R. 3 W.	Pan American Petroleum Corp., Pagosa-Jicarilla No. 1	Rio Arriba.
348	Sec. 7, T. 29 N., R. 5 W.	El Paso Natural Gas Company, No. 50 SJU 29–5	Rio Arriba.
350	Sec. 6, T. 28 N., R. 2 W.	Continental Oil Company, No. 1 South Dulce	Rio Arriba.
352	Sec. 33, T. 28 N., R. 1 E.	Derby Drilling Company, Jicarilla-Apache No. L	Rio Arriba.
365	Sec. 6, T. 23 N., R. 3 W.	Pan American Petroleum Corp., Jicarilla Tribal 72 No. 1	Rio Arriba.
367	Sec. 18, T. 23 N., R. 2 W.	Magnolia Petroleum, No. 1–A Jicarilla	Rio Arriba.
369	Sec. 27, T. 20 N., R. 20 W.	Humble Oil & Refining Company, Federal-Navajo No. 1	McKinley.
371	Sec. 26, T. 20 N., R. 11 W.	Sinclair Oil & Gas Company, No. 1 Santa Fe 205 Sargent	McKinley.
374	Sec. 16, T. 20 N., R. 6 W.	Sun Oil State "W" No. 1	McKinley.
377	Sec. 29, T. 19 N., R. 17 W.	Pure Oil Company, Coyote Canyon No. 1	McKinley.
380	Sec. 26, T. 19 N., R. 5 W.	Dome Petroleum Corp., Federal Tinian No. 26–1	McKinley.
381	Sec. 31, T. 19 N., R. 5 W.	James P. Dunigan, Inc., No. 1 Santa Fe	McKinley.
384	Sec. 5, T. 18 N., R. 5 W.	M.F. Abraham, Star Lake Unit No. 1	McKinley.
385	Sec. 12, T. 18 N., R. 5 W.	Gulf Oil Company–USA, Torreon Unit No. 1	McKinley.
387	Sec. 1, T. 17 N., R. 9 W.	Great Western Drlg. Company, No. 1 Hospah–Santa Fe	McKinley.
391	Sec. 3, T. 15 N., R. 19 W.	C.W. Beal & Assoc., Beal-Miller No. 1	McKinley.
392	Sec. 19, T. 15 N., R. 19 W.	Kerr-McGee Corp., Santa Fe No. 1	McKinley.
393	Sec. 8, T. 15 N., R. 13 W.	Tidewater Assoc. Oil Company, Mariano Dome No. 1	McKinley.
394	Sec. 15, T. 15 N., R. 12 W.	Reese & Jones, N2 15 No. 1	McKinley.
396	Sec. 4, T. 15 N., R. 6 W.	Richfield Oil Corp., No. 1 Drought-Booth	McKinley.
398	Sec. 14, T. 14 N., R. 10 W.	Stella Dysart, No. 14–1 Federal	McKinley.
399	Sec. 28, T. 14 N., R. 9 W.	Phillips Petroleum Company, Sandstone Minerals Water Well No. 1	McKinley.
400	Sec. 14, T. 14 N., R. 8 W.	Superior Oil Company, Gov't. No. 25–14	McKinley.
403	Sec. 10, T. 22 N., R. 6 W.	Sun Oil Company, El Paso Federal No. 1	Sandoval.
410	Sec. 13, T. 21 N., R. 5 W.	Union Oil Co. of California, Caldwell Ranch–USA–NM 0122353 No. 1–M–13	Sandoval.
416	Sec. 17, T. 20 N., R. 3 W.	Pan American Petroleum Corp., "C" USA No. 1	Sandoval.
426	Sec. 14, T. 19 N., R. 3 W.	Magnolis Petroleum Company, Hutchinson-Federal No. 1	Sandoval.
428	Sec. 36, T. 19 N., R. 2 W.	El Paso Natural Gas Company, Elliott State No. 1	Sandoval.
429	Sec. 22, T. 18 N., R. 4 W.	Reynolds Mining, No. 1 Torreon	Sandoval.
431	Sec. 24, T. 18 N., R. 3 W.	Sun Oil Company, Sandoval Federal No. 1	Sandoval.
434	Sec. 7, T. 17 N., R. 3 W.	Brinkerhoff Drilling Company, Cabezon Government 14–7 No. 1	Sandoval.
435	Sec. 26, T. 17 N., R. 3 W.	Shell Oil Company, Wright No. 41–26	Sandoval.
438	Sec. 10, T. 16 N., R. 2 W.	Enexco, Inc., Shirl No. 2	Sandoval.
439	Sec. 1, T. 15 N., R. 4 W.	Houston Oil & Minerals Corp., Booth Drought No. 2	Sandoval.
440	Sec. 15, T. 15 N., R. 1 W.	Avila Oil Company, Odlum No. 1	Sandoval.
441	Sec. 20, T. 15 N., R. 1 E.	The Ohio Oil Company, Government-Haines No. 1	Sandoval.
442	Sec. 20, T. 14 N., R. 1 W.	Humble Oil & Refining Company, Santa Fe Pacific B No. 1	Sandoval.
443	Sec. 10, T. 13 N., R. 3 W.	Texaco, Inc., Howard Major No. 1	Sandoval
444	Sec. 18, T. 13 N., R. 3 E.	Shell Oil Company, Santa Fe No. 1	Sandoval.

Table A2. Number, name, location, and source of outcrop measured sections used for this study
[Grouped by State, County, township, range, and section. Sections not listed were not measured in Permian or Pennsylvanian rocks. Locations of sections shown by number on plate 1*A*]

No.	Section name	Location	County	Source
		Colorado		
15	Hermosa	Sec. 26, T. 37 N., R. 9 W.	La Plata	Wengerd and Matheny (1958).
18	Durango	Sec. 22, T. 36 N., R. 9 W.	La Plata	Baars (1962).
23	Mosca Creek	Sec. 17, T. 36 N., R. 5 W.	Archuleta	Condon and others (1984).
25	Piedra River	Sec. 17, T. 35 N., R. 4 W.	Archuleta	Read and others (1949).
		Arizona		
34	Canyon del Muerto	Sec. 14, T. 6 N., R. 8 W.	Apache	Read and Wanek (1961).
35	Monument Canyon	Sec. 32, T. 5 N., R. 8 W.	Apache	Read and Wanek (1961).
36	Buell Park	Sec. 25, T. 3 N., R. 6 W.	Apache	Read and Wanek (1961).
39	Bonito Canyon	Sec. 34, T. 1 N., R. 6 W.	Apache	Read and Wanek (1961).
42	Hunters Point	Sec. 23, T. 25 N., R. 30 E.	Apache	Read and Wanek (1961); J.D. Stanesco (unpub. data, 1986).
44	Oak Springs	Sec. 9, T. 24 N., R. 30 E.	Apache	Read and Wanek (1961).
46	Black Creek North	Sec. 2, T. 23 N., R. 30 E.	Apache	Read and Wanek (1961).
47	Black Creek South	Sec. 18, T. 23 N., R. 30 E.	Apache	Read and Wanek (1961).
		New Mexico		
85	McGaffy	Sec. 28, T. 14 N., R. 16 W.	McKinley	Baars (1962).
89	McGaffy	Sec. 3, T. 13 N., R. 16 W.	McKinley	Read and Wanek (1961).
97	Vallecito del Puerco	Sec. 25, T. 21 N., R. 1 W.	Sandoval	Wood and Northrop (1946).
100	Senorito Canyon	Sec. 6, T. 20 N., R. 1 E.	Sandoval	Wood and Northrop (1946).
103	Red Top	Sec. 2, T. 19 N., R. 1 E.	Sandoval	Wood and Northrop (1946).
105	Guadalupe Box	Sec. 36, T. 18 N., R. 1 E.	Sandoval	Wood and Northrop (1946).
107	Pinos and Penasco Canyons	Sec. 5, T. 16 N., R. 1 E.	Sandoval	Armstrong and Holcomb (1989).
108	Arroyo Penasco	Sec. 21, T. 16 N., R. 1 E.	Sandoval	Wood and Northrop (1946).
110	Bluewater	Sec. 29, T. 12 N., R. 12 W.	Cibola	Baars (1962).
113	Cottonwood Creek	Sec. 2, T. 11 N., R. 14 W.	Cibola	Read and Wanek (1961).

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