Geology of Pre-Pennsylvanian Rocks in the Paradox Basin and Adjacent Areas, Southeastern Utah and Southwestern Colorado

U.S. GEOLOGICAL SURVEY BULLETIN 2000-G

On the Front Cover. View south toward the La Sal Mountains along the Colorado River between Cisco and Moab, Utah. Fisher Towers in center is composed of Permian Cutler Formation and capped by Triassic Moenkopi Formation. The prominent mesa at left center is capped by Jurassic Kayenta Formation and Wingate Sandstone and underlain by slope-forming Triassic Chinle and Moenkopi Formations. The Chinle-Moenkopi contact is marked by a thin white ledge-forming gritstone. The valley between Fisher Towers and Fisher Mesa in the background is part of Richardson Mesa, part of Professor Valley. Photograph by Omer B. Raup, U.S. Geological Survey.

Geology of Pre-Pennsylvanian Rocks in the Paradox Basin and Adjacent Areas, Southeastern Utah and Southwestern Colorado

By Steven M. Condon

EVOLUTION OF SEDIMENTARY BASINS—PARADOX BASIN

A.C. Huffman, Jr., Project Coordinator

U.S. GEOLOGICAL SURVEY BULLETIN 2000–G

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

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METRIC CONVERSION FACTORS

Multiply	By	To obtain
Miles	1.609	Kilometers
Feet	0.3048	Meters
Inches	2.54	Centimeters

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ABSTRACT

The oldest rocks in the Paradox Basin of the southwestern United States are an Early Proterozoic crustal sequence of gneiss and schist, approximately 1,800–1,740 Ma. The complex was intruded by Early to Middle Proterozoic (1,730–1,700 Ma and 1,435–1,400 Ma) plutonic igneous rocks and is overlain by supracrustal Middle Proterozoic (1,695–1,435 Ma) sedimentary rocks in some places. A younger Middle to Late Proterozoic (1,250–800 Ma) sequence of metasedimentary rocks may be present in parts of the western Paradox Basin. Early Proterozoic rocks in the Paradox Basin and adjacent areas accumulated in a convergent plate setting on the edge of the Archean craton. The possible Middle to Late Proterozoic rocks may have been deposited in a lacustrine setting.

A wedge of clastic and carbonate Cambrian rocks unconformably overlies basement rocks. Cambrian rocks are thickest on the west side of the study area and thin eastward. From oldest to youngest, Cambrian units are the Tintic Quartzite, Ophir Formation, Maxfield Limestone, Lynch Dolomite, and Ignacio Quartzite.

In the Paradox Basin, Upper Devonian rocks unconformably overlie Cambrian strata; Ordovician and Silurian rocks are not known in this area. A basal Devonian unit, the Aneth Formation, is areally restricted and only is present near the Four Corners. Overlying the Aneth, probably unconformably, is the Elbert Formation. In much of the Paradox Basin the basal member of the Elbert is the McCracken Sandstone Member. Overlying the McCracken is a shale and dolomite member known informally as the upper member. The youngest Devonian unit in the basin is a carbonate rock, the Ouray Limestone.

An unconformity separates Devonian from Mississippian rocks in the Paradox Basin. In the eastern part of the basin Mississippian rocks are known as the Leadville Limestone, and in the western part this carbonate unit is known as the Redwall Limestone.

Mississippian rocks are in turn unconformably overlain by Pennsylvanian rocks in the Paradox Basin. In most areas the Molas Formation, which includes a basal regolith, overlies Mississippian strata. In a few areas the Molas is missing, and Mississippian strata are overlain by carbonate rocks of the Hermosa Group.

All of the Phanerozoic sedimentary rocks of the Paradox Basin were deposited on a stable cratonic shelf on the trailing edge of the continent. Uppermost Cambrian, Devonian, and Mississippian rocks were deposited in warm, shallow-marine environments. Low to moderate topography east of the study area, associated with the Transcontinental arch, provided clastics to the shelf during deposition of the Tintic and Ignacio Quartzites and the Elbert Formation. The pre-Pennsylvanian sedimentary wedge thickens markedly to the west into the Cordilleran miogeocline.

INTRODUCTION

This study was funded as a part of the U.S. Geological Survey's Evolution of Sedimentary Basins program. The Paradox Basin of southeastern Utah and southwestern Colorado was the subject of a multidisciplinary investigation of the stratigraphy, sedimentology, geochemistry, and structure of the basin. In this report I describe the geology of Precambrian through Mississippian rock units in the Paradox Basin, mainly on the basis of a study of geophysical well logs (pl. 1). My main emphasis is the lithology and stratigraphic correlations of Cambrian through Mississippian formations; however, I describe the lithology of the Precambrian basement as revealed by deep wells and at scattered outcrops at the margins of the basin.

Acknowledgments.—Jean Dillinger digitized the base maps used for the maps presented here. Critical reviews by J.A. Campbell and K.B. Ketner greatly improved the manuscript. Discussions of Cambrian and Devonian rocks with J.A. Campbell and C.A. Sandberg were very helpful in my gaining an understanding of those units.

GEOGRAPHIC AND STRUCTURAL SETTING

The Paradox Basin is an oval area in southeastern Utah and southwestern Colorado that, for this study, is defined by

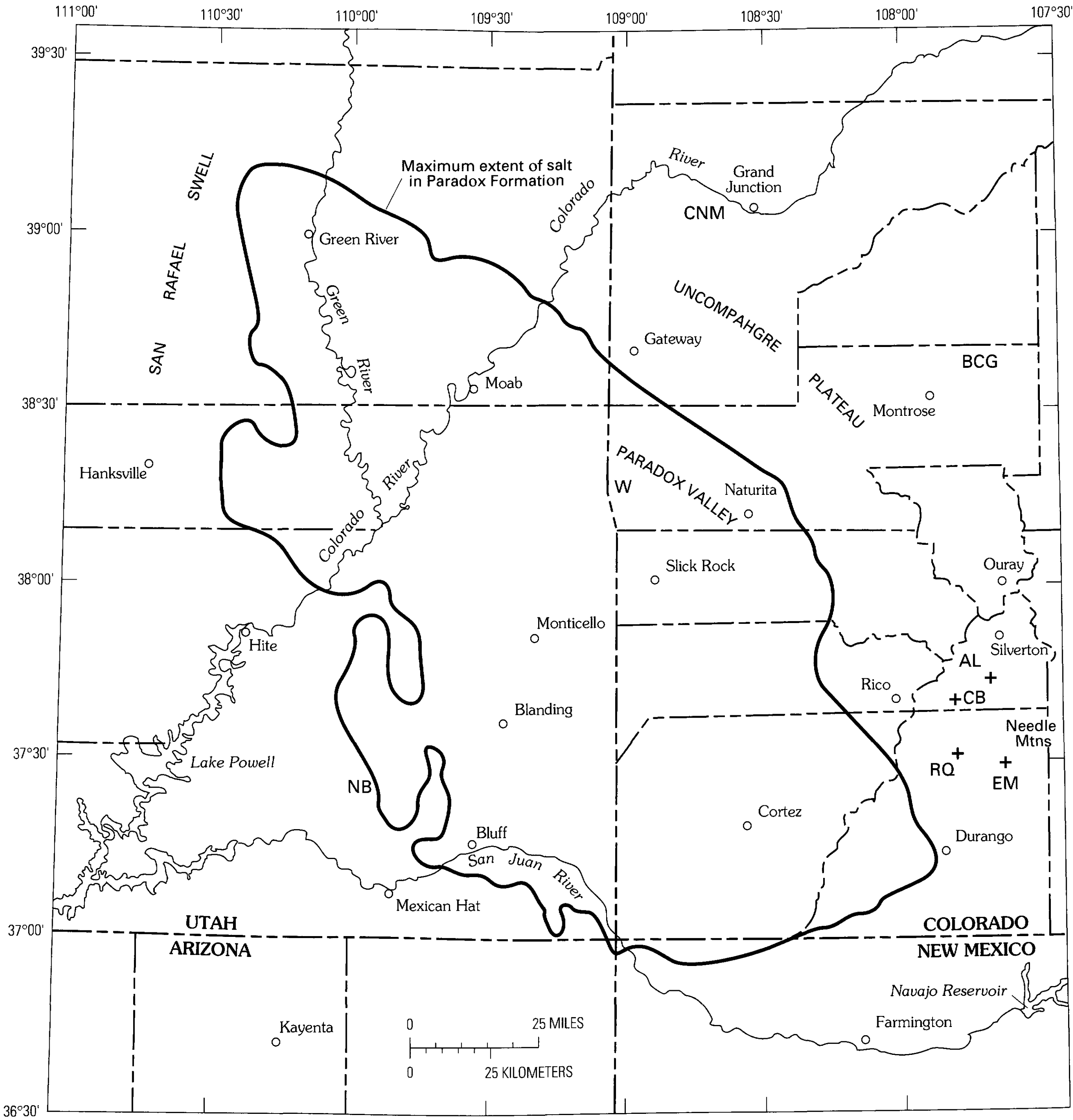


Figure 1. Map showing geographic features of the Paradox Basin and adjacent areas. Abbreviations for geographic locations: **AL**, Andrews Lake; **BCG**, Black Canyon of the Gunnison National Monument; **CB**, Coal Bank Pass; **CNM**, Colorado National Monument; **EM**, Endlich Mesa; **NB**, Natural Bridges National Monument; **RQ**, Rockwood Quarry; **W**, Wray Mesa.

the maximum extent of salt in the Middle Pennsylvanian Paradox Formation (fig. 1). Using this definition, the basin has a maximum northwest-southeast length of about 190 mi, and a northeast-southwest width of about 95 mi. The basin in which the salt was deposited was primarily a Pennsylvanian and Permian feature that accumulated thick deposits of carbonate, halite, sandstone, and arkose in response to tectonic downwarping and simultaneous uplift along its northeastern border.

In the context of this report, the term "Paradox Basin" means more than just the Pennsylvanian and Permian depositional basin. It refers to the geographical area covered by the salt as shown in figure 1, including topographic and structural features at the surface today. In this report I focus on the pre-Pennsylvanian stratigraphic units that underlie the salt, even though the depositional limits of those units do not correspond to the salt limits. The Paradox Basin, as thus recognized, is in the central part of the Colorado Plateau. The shape of the basin was modified and obscured by later tectonic events, primarily the Laramide orogeny. Today, the basin has been dissected in places by uplift of the Colorado Plateau and by downcutting of the Colorado River and its tributaries. The name "Paradox Formation" originated with Baker and others (1933) for exposures of the unit in Paradox Valley, Montrose Co., Colo. The valley and town of Paradox were named long before the formation was named and probably were so named because the Dolores River cuts through the south valley wall, runs transversely across the valley at right angles to the northwest trend of the valley, and exits through the north valley wall. The relation of the river to the valley is thus, seemingly, a paradox (Hite and Buckner, 1981).

The basin is bordered on the northeast by the Uncompahgre Plateau, a broad anticline cored by Precambrian rocks (fig. 2). The east side of the basin is bounded by the San Juan dome, an area that is covered, in part, by Tertiary volcanic rocks. In the Needle Mountains, a prominent feature of the southern San Juan dome, Precambrian rocks are widely exposed. The southeastern end of the basin is defined by the northeast-trending Hogback monocline that extends southwestward from the Durango, Colo., area through northwestern New Mexico. The southern and southwestern border of the Paradox Basin is rather ill defined topographically, extending northwestward from Four Corners (the junction of Utah, Colorado, New Mexico, and Arizona) across the Monument upwarp to the Henry Basin. The northwestern side is bounded by the San Rafael Swell, and the far northern end of the basin merges with the southern side of the Uinta Basin.

Structural and physical features of the Paradox Basin within the area defined by the salt (figs. 1, 2) are very diverse. The northern part of the basin has been termed the "Paradox fold and fault belt" (Kelley, 1958b). This area consists of a series of roughly parallel, northwest-trending faults, anticlines, and synclines. The northeastern part of this division is more complexly folded, and some anticlines have been pierced by salt from the Paradox Formation. Dissolution of salt in the center of some anticlines in this region has caused downfaulting and the formation of grabens along the anticlinal crests. Rocks as old as Pennsylvanian are exposed in the cores of some of the anticlines, and remnants of Cretaceous rocks are present in some synclines and in collapsed blocks within some anticlines. The southwestern part of this division is also faulted and folded but lacks the complex piercement structures of the northeastern part.

South of the fold and fault belt are the Blanding Basin and the Four Corners platform (fig. 2). The Blanding Basin is a generally undeformed area in which Jurassic and Cretaceous rocks are at the surface. The Four Corners platform is a structurally high bench that separates the Paradox and San Juan Basins. The platform has mainly Cretaceous rocks at the surface. The Hogback monocline defines the southeastern side of the Four Corners platform.

The southwestern part of the Paradox Basin is dominated by the Monument upwarp. This area consists of deep canyons and high mesas that provide the setting for part of Canyonlands National Park, Natural Bridges National Monument, and other recreation and cultural resource areas for which southeastern Utah is famous. The upwarp trends generally north and is a broad anticline. It is bounded on the east by the steeply dipping Comb Ridge monocline and merges to the west with the Henry Basin across the White Canyon slope. A northeast-trending anticline along the Colorado River extends beyond the Monument upwarp into the fold and fault belt. Permian and some Pennsylvanian rocks are widely exposed on the upwarp and along the river.

Adding to the picturesque qualities of the Paradox Basin are the intrusive rocks of the La Sal, Abajo, and Sleeping Ute Mountains within the basin and intrusive centers such as the Henry, Carrizo, La Plata, Rico, and San Miguel Mountains in surrounding areas. These intrusive rocks are Late Cretaceous to Tertiary in age, and their intrusion deformed the enclosing sedimentary rocks into broad domes.

The tectonic setting of the western United States in Cambrian through Devonian time was quite different than that in Mississippian time. At the earlier time Utah was divided roughly in half by the Wasatch hinge line, a feature still prominent today. This line extends through the southern tip of Nevada north-northeasterly to the southeastern corner of Wyoming and beyond. Early Paleozoic sedimentation west of this line was in a deep basin that encompassed western Utah, eastern Nevada, and adjacent areas to the north and south (Burchfiel and others, 1992; Poole and others, 1992). Sedimentation east of the line was on a stable shelf in mainly shallow marine conditions (figs. 3, 4). The tectonic setting changed radically in the latest Devonian and Mississippian. At that time eastward-directed compression led to development of the Antler orogenic highland in central Nevada that shed terriginous clastic sediment eastward (Poole and Sandberg, 1991). The area of the Paradox Basin was, however, far enough away from this tectonic activity that it remained on a shallow cratonic shelf. Most of the rock units discussed in this report reflect deposition on this stable shelf and are tabular units. Marine correlatives in central Colorado and northwestern New Mexico of many of the pre-Pennsylvanian rocks indicate that shelf conditions extended some distance eastward from the Paradox Basin.

The current structural configuration of the basin and surrounding area is shown on plate 2, a structure contour map drawn on top of the Mississippian Leadville and Redwall Limestones. This horizon was chosen because (1) it shows the structure at the top of the package of rocks that is the subject of this report and (2) the data set for the horizon is the most complete for any stratigraphic unit in the basin. Older stratigraphic units are generally less suitable because of the fewer wells that penetrated those units, and younger stratigraphic units are commonly eroded and incomplete, making them less useful for a structure contour map.

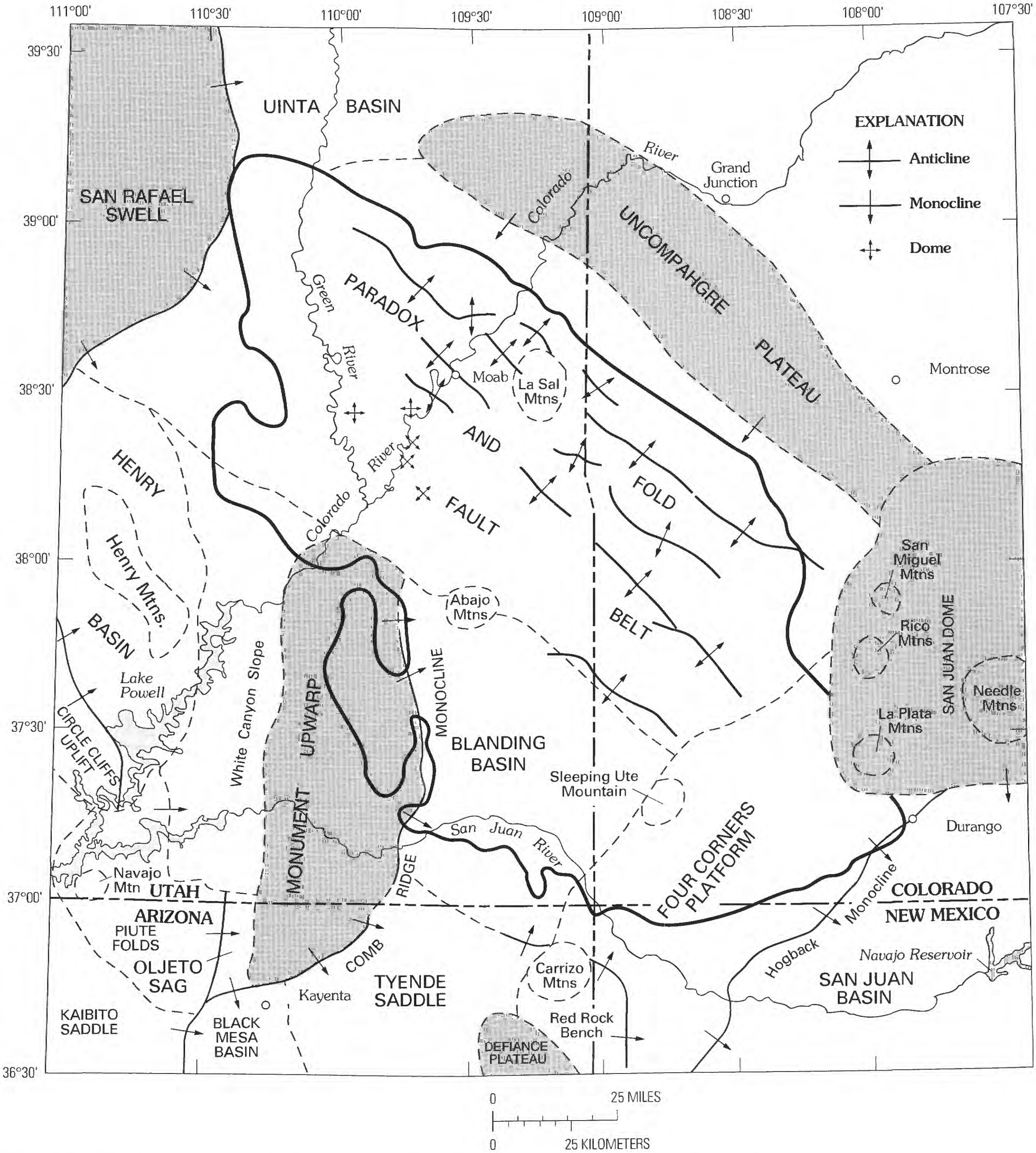


Figure 2. Map showing structural elements of the Paradox Basin and adjacent areas. Dashed lines indicate transitional or indefinite boundaries between elements. Modified from Kelley (1958a, b).

Plate 2 shows, clockwise from upper left, (1) the high area of the San Rafael Swell, (2) the high area of the Uncompahgre Plateau, flanked on its southwest by the deepest part of the Paradox Basin, (3) McElmo dome west of Cortez, Colo., (4) the low area of the San Juan Basin in northwestern New Mexico, (5) the high area of the northern Defiance Plateau in northeastern Arizona, and (6) the high area of the Monument upwarp in southeastern Utah. The sharp flexure of Comb Ridge monocline is clearly evident on the eastern side of the Monument upwarp. Also evident

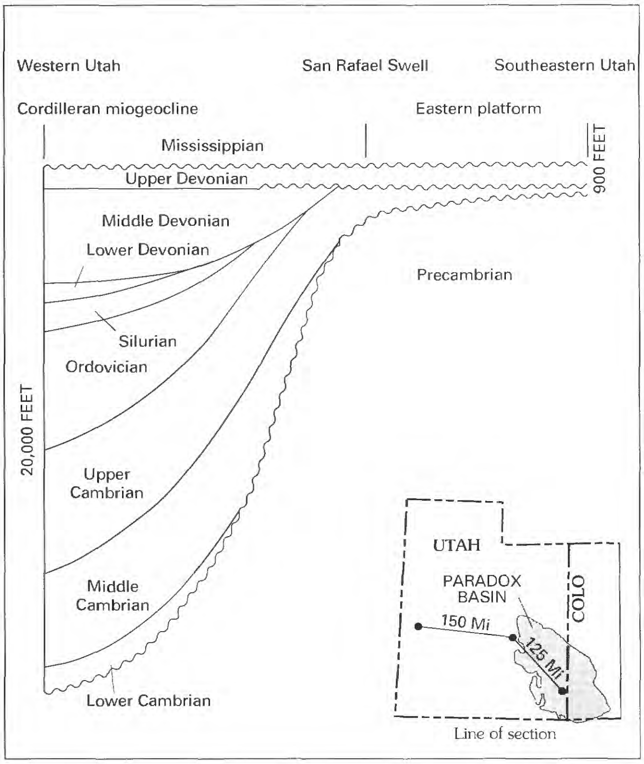


Figure 3. Diagrammatic cross section of Cambrian through Devonian rocks from southeastern to western Utah. Modified from Stokes (1986).

is the structural nose that extends northeastward from the northern end of the Monument upwarp along the Colorado River into the fold and fault belt.

PREVIOUS STUDIES

The remoteness and inaccessibility of much of the Paradox Basin served to isolate it from the scrutiny of geologists until the latter half of the 19th century. Powell's historic voyages down the Green and Colorado Rivers were the first detailed accounts of the area (Powell, 1875). The Henry Mountains, just west of the basin, were the last major mountains discovered in the American West.

Whitman Cross and his associates studied the rocks of the San Juan Mountains of southwestern Colorado at about the turn of the century and were among the first to describe the pre-Pennsylvanian rocks that are now known to underlie most of the Paradox Basin. They established much of the nomenclature (fig. 5) for Precambrian, Cambrian, and Devonian units in the eastern part of the basin (Cross, Spencer, and Purington, 1899; Cross, 1901, 1904, 1907; Cross, Howe, and Ransome, 1905; Cross, Howe, Irving, and Emmons, 1905; Cross, Howe, and Irving, 1907; Cross and Hole, 1910).

Interest in the water and mineral resources and oil and gas possibilities of southeastern Utah prompted studies from the early 20th century to the 1940's. Key reports from this period include Longwell and others (1923), Baker and others (1927, 1936), Gilluly and Reeside (1928), Baker (1933, 1936, 1946), Dane (1935), Gregory, (1938), and McKnight (1940). These studies were directed mainly toward mapping the surface rocks and structures because of the paucity of deep drilling in the basin at that time. They did provide the basic geologic framework of the basin, which has been refined by subsequent geologic studies.

One of the earliest oil fields in Utah was discovered in 1908 at Mexican Hat (Lauth, 1978), and wildcat drilling took place in many areas of the basin through the mid-1950's. Discovery of the giant field at Aneth, southeast of Bluff, Utah, in 1956 (Matheny, 1978) accelerated deep drilling in the basin. Deep wells throughout the basin provide the data on which much of the present report is based.

Numerous reports on the pre-Pennsylvanian rocks of the Paradox Basin have been published from the mid-1950's to the present. Those that were invaluable in the preparation of the present report are cited, as appropriate, in later sections. Of particular note is the large and still-growing volume of work concerning Precambrian rocks of this region. Advances in isotopic dating have greatly aided in the interpretation of the Proterozoic history of the southwestern United States.

METHODS

The main sources of data for this study are geophysical logs from wells drilled throughout the Paradox Basin and surrounding areas (appendix 1). A collection of paper logs was purchased and was used as the basis for the correlations and maps presented here. Types of logs include gamma-ray, neutron, spontaneous potential, resistivity, conductivity, and interval transit time (sonic).

Supplementing the geophysical logs were sample logs from the American Stratigraphic Company (AMSTRAT). These sample logs were used to match specific lithologies to the geophysical log responses. In addition, AMSTRAT logs were important in compiling the lithology of Precambrian rocks in the study area. One hundred and twenty-five AMSTRAT logs were examined for descriptions of pre-Pennsylvanian stratigraphic units; an additional ninety logs were examined to check the lithology of only basement rocks. Because some of the paper sample logs were not available to me, the cuttings of 40 wells, stored at the U.S. Geological Survey (USGS) Core Research Center in Denver, Colo., were examined. Also examined at the research center was a core of pre-Pennsylvanian units from a well in southwestern Colorado.

A database, compiled by Rocky Mountain Geological Databases, Inc. (RMGD), was of help in gathering information on the wells used for this study. This database includes all known wells that penetrate Pennsylvanian and older units

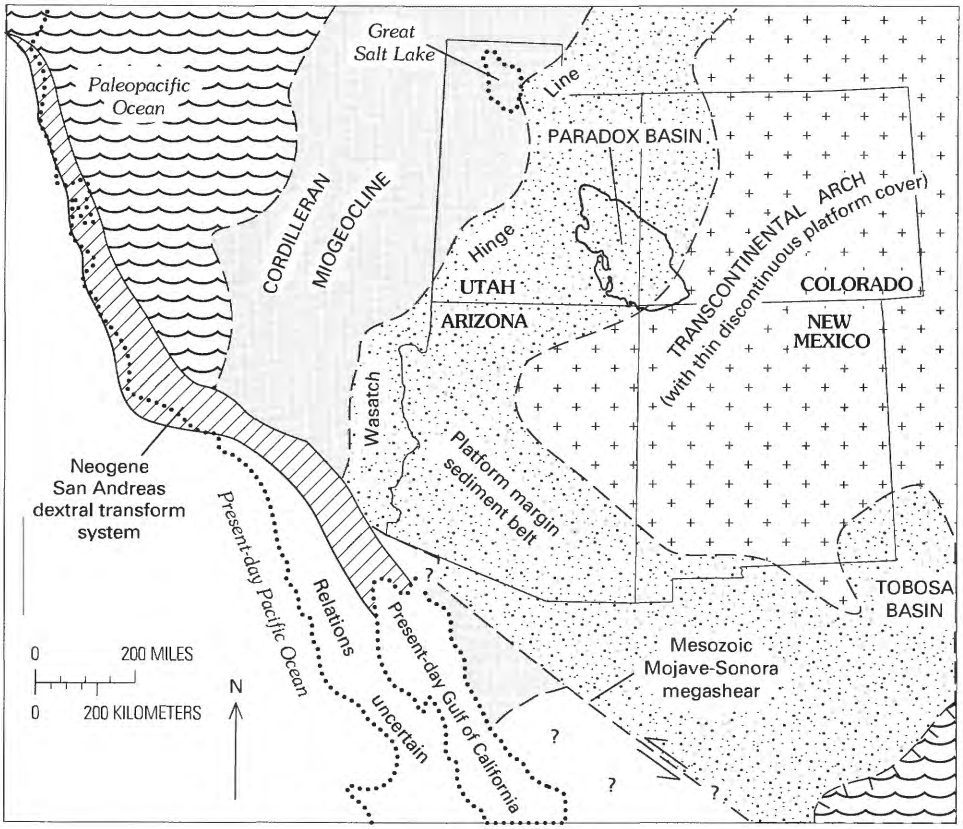


Figure 4. Map showing paleogeography of the southwestern United States during deposition of Cambrian through Devonian strata. Stippled pattern indicates platform-margin sediment belt. Modified from Dickinson (1989).

in the Paradox Basin and adjacent areas. The database was purchased for use in this and other studies of the Paradox Basin Evolution of Sedimentary Basins Project. The picks of stratigraphic tops as given in the database were used as a guide when starting on this study of pre-Pennsylvanian rocks; however, I changed many of the picks in the database (most changes are minor) and take full responsibility for the correlations presented herein.

Other sources of data were reports concerning pre-Pennsylvanian rocks in the Paradox Basin area. Surface rocks have been studied previously by other geologists, and thus lithologies and thicknesses of outcrop units in areas not visited by the author were available (appendix 2). Published isopach maps and cross sections of subsurface units were consulted to see how other workers portrayed the units. The geologic maps of Colorado (Tweto, 1979) and Utah (Hintze, 1980) were used to gather control points concerning the elevation of the Precambrian surface and in estimating thicknesses of stratigraphic units on the Uncompahgre Plateau and in the Needle Mountains.

I examined a few outcrops of pre-Pennsylvanian rocks. Precambrian rocks were examined near the Colorado-Utah State line on the Uncompahgre Plateau, in Unaweep Canyon, northeast of Gateway, Colo., and in the Needle Mountains. Cambrian, Devonian, and Mississippian units were also examined at various places near the Needle Mountains.

The isopach and structure maps compiled for this report were constructed using a program called Interactive Surface Modeling (ISM), marketed by Dynamic Graphics, Inc. A base map was digitized to provide a geographic base for the other maps, and then individual files that contain location and thickness data were gridded and contoured.

Computer contouring is, by its nature, an averaging process that is dependent on two factors: (1) the quality of the data input into the program and (2) the method used to calculate the contours. The quality of the input data is itself made up of several factors, including, but not limited to (1) the number of control points used, (2) the distribution of the control points, (3) the number of stratigraphic units penetrated by each well, and (4) the accuracy of picks made by the investigator.

The detail shown by the isopach maps would have been greater if more logs had been used; however, budget and time constraints limited the data set to the selected subset of wells. Because of this, the maps and cross sections provide an overview of the geology of the basin rather than a detailed analysis of local areas. The area of salt anticlines, in the

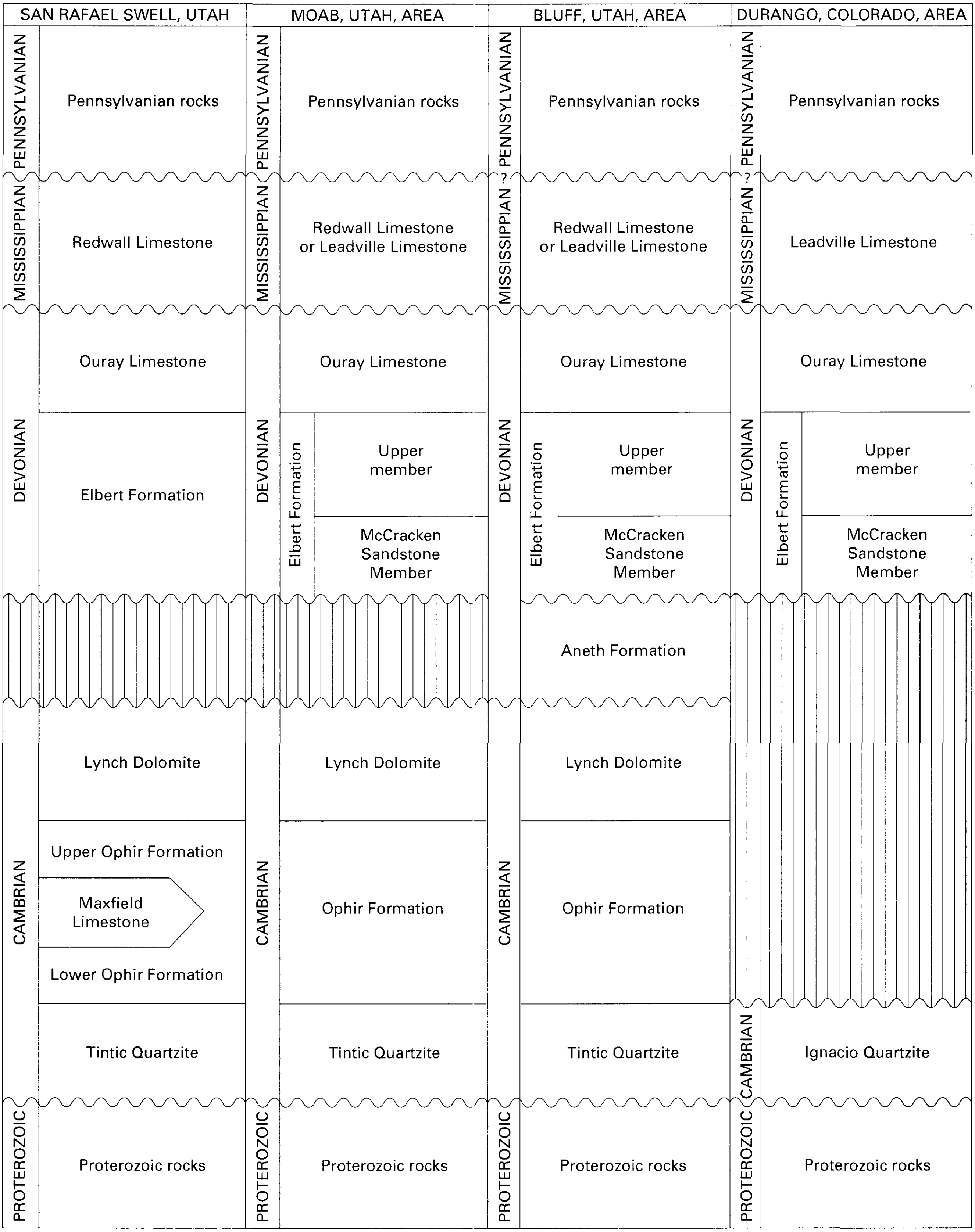


Figure 5. Nomenclature of Cambrian through Mississippian rocks at selected locations in the Paradox Basin and adjacent areas. Stratigraphic units between columns are only approximately time equivalent. Compiled from various sources, including Lochman-Balk (1958, 1972), Merrill and Winar (1958), Parker and Roberts (1966), and Sandberg and others (1989).

northeastern part of the basin, is especially complex, both structurally and stratigraphically.

The problems of mapping in the northeastern part of the basin can perhaps be more fully appreciated by considering an isopach map representing building height in a metropolitan downtown area. If the control points only consist of one building height per block, then the map will show an average increase in height compared with surrounding residential areas but will not show the true detail of the downtown area. On the other hand, if the height of each individual building is known, the isopach map will be much more accurate. The same considerations apply to the Paradox Basin, where true structural and stratigraphic complexities are masked by the lack of control points.

The methods used for computer contouring vary according to the program used. In the ISM program used for this study, a grid is first constructed that is the basis for the contour lines. A grid defines a surface in three-dimensional space that is calculated from the input scattered-data (x, y, z) coordinates. The area shown on the maps was divided into a grid matrix of 300 rows and 300 columns. This is equivalent to a grid spacing in the x direction (longitude) of about 0.75 miles and a grid spacing of about 0.9 miles in the y direction (latitude).

Each grid node (intersection points between grid lines) is calculated in two steps: (1) initial estimation of grid node values and (2) biharmonic iterations using scattered-data feedback. The initial estimate is made by dividing the two-dimensional x,y space into octants centered on each grid node (Dynamic Graphics, Inc., 1988). Scattered-data points are selected within each octant depending on their distribution. Nearby points are used first within each octant, and the program will not search past two points in adjacent octants to calculate an empty octant; however, if no data are near a grid node, the program will search to the edge of the data set to find data. Once the points are selected, they are averaged using an inverse distance algorithm, in which the weighting is dependent on the angular distribution of the points.

After this initial estimate is made, ISM uses a biharmonic cubic spline function to fit a minimum tension surface to the grid nodes. To ensure that the minimum tension surface honors the scattered data as accurately as possible, a scattered-data feedback procedure is used to keep grid nodes tied to neighboring scattered data. In this study, as many as eight scattered-data points that fall within one-half cell of a grid node were used in this feedback procedure.

Once the minimum tension grid surface is calculated, ISM can use the grid to construct contour maps, cross sections, and perspective views of surfaces. It is essential to keep in mind that the final products are calculated from the grid values, not from the scattered data. Thus there is some degree of averaging of the original data in constructing the contour maps.

The point of this discussion of techniques, and the relevance to the present study, is to illustrate that the contour maps presented herein were constructed using a consistent set of procedures that result in repeatable results. This method differs from hand-contouring methods because in the latter techniques the geologist commonly contours using a set of ill-defined and inconsistently applied procedures that introduce biases according to the individual's intent. This is not to say that a hand-contoured map is any less accurate than a computer-generated map. An individual's knowledge of an area is essential to the successful portrayal of a unit that is present in the subsurface and that is only known at scattered control points.

One of the shortcomings of computer-generated contour maps is that in areas of widely spaced control points, the importance of some data values may be exaggerated. For example, in one area of Colorado the Devonian Ouray Limestone and the Mississippian Leadville Limestone were apparently eroded from the top of an anticline sometime during the Pennsylvanian. The thickness values at that control point for those units are therefore zero. Because there are no other control points clustered nearby, the area of zero thickness for the Ouray and Leadville is probably shown larger than is real. It seems reasonable to infer that the erosion was limited to the crest or flanks of the anticline and was of fairly limited extent. The computer, however, knows nothing of the anticline and only considers the other nearest control points, thus exaggerating the area of erosion. Rather than disregarding computer-generated maps as useless and going back to the "old fashioned method of eyeballing," the limitations of computer maps need to be recognized and taken into consideration in any analysis of the data.

Two data sets, with some overlap, were used to construct the maps for this report. The data set for the Precambrian lithology and structure maps consists of 151 wells in the study area. These were all the wells either by AMSTRAT or RMGD, identified as reaching Precambrian rocks. The other data set consists of holes chosen mainly for correlation of Cambrian through Mississippian stratigraphic units, of which there are 177. Thirty-three of the wells are common to both data sets, resulting in a total number of 295 wells used for this study (pl. 1, appendix 1).

Many of the logs from these wells were digitized to construct regional cross sections (figs. 6–9). These logs show the picks of units used for this report, as well as the distribution of units across the basin. The locations of the sections are shown on plate 1.

PRECAMBRIAN ROCKS

Precambrian rocks of Proterozoic age underlie most of the Paradox Basin. The exceptions are the intrusive centers of the La Sal, Abajo, Sleeping Ute, and La Plata Mountains, where igneous rocks of Late Cretaceous to early Tertiary age extend to an unknown depth. Proterozoic rocks are exposed at the surface on the northeastern side of the basin on the Uncompahgre Plateau and in the adjacent Colorado River gorge and east of the basin in the Needle Mountains area of southwestern Colorado. Many different names and methods of classification have been used in the study of the Colorado rocks (Edwards, 1966; King, 1976; Hedge and others, 1986; Tweto, 1987). The classification system of Tweto (1987) is used in this report, and the following descriptions draw from his report. Other overviews of outcropping Precambrian rocks in southwestern Colorado are by Dane (1935), Mose and Bickford (1968), Barker (1969), Cater (1970), Condie (1981, 1992), Grambling and Tewksbury (1989), and Gonzales and others (1994). Several papers in Reed and others (1993) summarize the Proterozoic stratigraphy and tectonic history of this area.

Proterozoic rocks in the subsurface of the Paradox Basin are probably as diverse as those exposed at the surface in southwestern Colorado. Unfortunately, the closest other exposures of Precambrian rocks are on the Defiance Plateau to the south, at the Grand Canyon to the southwest, in western Utah or in the Wasatch Mountains to the west and northwest, and in the Uinta Mountains to the north. These outcrops are too far from the Paradox Basin to provide much insight into the lithology of the Precambrian in the subsurface of the basin. Scattered deep drilling and geophysical studies in the basin are our only clues as to the lithology of the basement in that area. As part of the Evolution of Sedimentary Basins program V.J.S. Grauch is conducting gravity and magnetic studies in the basin (V.J.S. Grauch, oral commun., 1994).

OUTCROPPING PROTEROZOIC ROCKS

In Colorado Early Proterozoic basement rocks are crystalline gneiss and schist that were termed the "gneiss complex" by Tweto (1987, p. A10). This complex was further divided into two main lithologies, biotitic gneiss and felsic and hornblendic gneiss, although a great variety of rock types are present, depending on the parent rock and the degree of metamorphism. Various rock types are complexly interbedded in some areas. The gneiss complex is the precursor rock into which igneous rocks were emplaced and on which younger Precambrian and Phanerozoic rocks were deposited. The protoliths were a combination of sedimentary, plutonic, and volcanic rocks that were metamorphosed in several episodes at about 1,740, 1,700, and 1,650–1,600 Ma (Bowring and Karlstrom, 1990). On the basis of dates obtained from metavolcanic rocks, the age of the gneiss complex is thought to be no older than about 1,800 Ma (Tweto, 1987, p. A11).

The biotitic gneiss was derived mainly from sedimentary rocks. This lithology is composed of dark-colored biotite-quartz-plagioclase gneiss and schist and other less abundant rock types. Biotitic gneiss occupies a broad area across central Colorado and extends southwestward to outcrops on the northeastern side of the study area. Outcrops in the Colorado National Monument, near Grand Junction, Colo., and most outcrops at the Black Canyon of the Gunnison National Monument, east of Montrose, Colo. (fig. 1), are composed of biotitic gneiss and schist (Tweto, 1987, pl. 1). The rocks at the Gunnison River are called the Black Canyon Schist (Hunter, 1925). In some areas quartzite makes up much of this unit, although some of the quartzite bodies may be younger than the gneiss and schist (Reed and others, p. 213, *in* Van Schmus and others, 1993). The biotite gneiss is included in what was termed the Idaho Springs–Black Canyon assemblage by Condie (1992, p. 459). Rocks of similar lithology and age are exposed in the Mineral Mountains of south-central Utah (Aleinikoff and others, 1986).

The felsic and hornblendic gneisses were derived mainly from volcanic and related intrusive rocks. The felsic gneiss is diverse but in general is light colored and is composed of quartz, plagioclase, and potassium feldspar. It was derived in large part from tuffs and volcaniclastic rocks but also from plutonic rocks in the Needle Mountains (Gonzales and others, 1994). The hornblendic gneiss is dark-colored amphibolite and greenstone of basaltic composition. It crops out in Unaweep Canyon, northeast of Gateway, Colo., and in the Needle Mountains, north of Durango (Tweto, 1987, pl. 1). Named rocks of the felsic and hornblendic gneiss types in the Needle Mountains are the Twilight Gneiss and the Irving Formation, respectively. Field relations first noted by Cross, Howe, Irving, and Emmons (1905) suggest that the Twilight Gneiss is an intrusive complex emplaced into the Irving Formation during an extensional event (Gonzales and others, 1994). Except for the exposure in Unaweep Canyon, felsic and hornblendic gneisses do not extend north of about the latitude of Ouray, Colo., in the Colorado part of the study area.

Early Proterozoic rocks in the southwestern United States are thought to have accumulated at a convergent plate boundary adjacent to the Archean craton of Wyoming (Barker and others, 1976; Condie, 1982, 1986, 1992; Reed, 1987; Dickinson, 1989). This area was referred to as the "Inner Accretionary belt" by Van Schmus and others (1993, p. 274). A combination of continent-edge rifting and subduction and island arc subduction was proposed by Condie (1982). Consolidation of several magmatic arcs was described by Condie (1982, 1986, 1992) and was considered to be the source of the volcaniclastic and submarine volcanic rocks of the felsic and hornblendic gneiss complex. Condie (1992, p. 459) interpreted the biotitic gneiss complex as the product of sedimentation in a continental back-arc basin. Aleinikoff and others (1993) concluded that the Proterozoic rocks in central Colorado were derived from juvenile, noncontinental material; that is, they were not sourced from the older Archean terrane in Wyoming. Anderson (1989a, b) presented a detailed account of the development of the

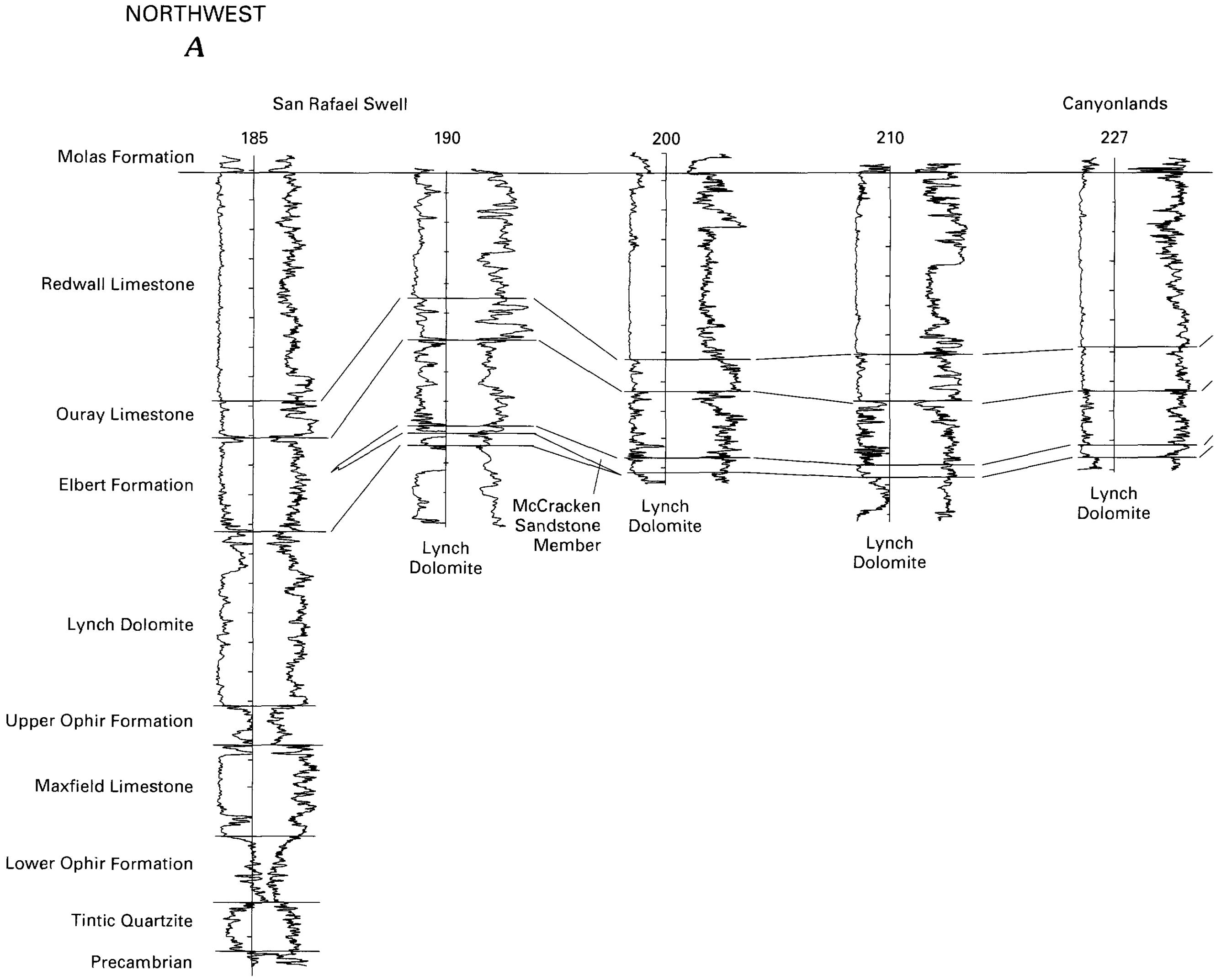


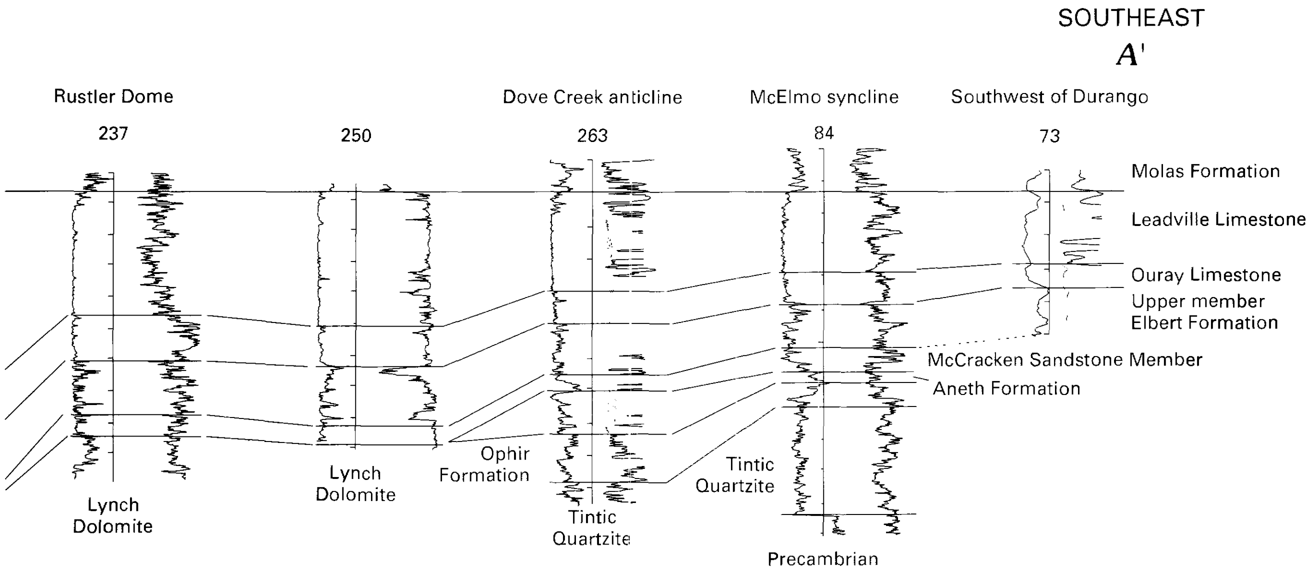
Figure 6 (above and facing page). Cross section of pre-Pennsylvanian units from the San Rafael Swell, Utah, to the Durango, Colo., area along the axis of the Paradox Basin. Numbers above the well logs correspond to those on plate 1 and in appendix 1. All logs are gamma ray-neutron, except for number 73, which is spontaneous-potential and resistivity. Vertical ticks are every 100 ft; horizontal scale is variable. Line of section shown on plate 1.

Proterozoic crust in Arizona, in a setting similar to that in Colorado. Although slightly to the north of the area discussed by Anderson, the Paradox Basin was subject to similar processes during formation of the Proterozoic crust.

Proterozoic rocks in central Arizona were divided into named tectonostratigraphic provinces by Karlstrom and Bowring (1988). Each province is composed of smaller *blocks* that share lithologic and tectonic similarities. The blocks are grouped into *terranes* that form a segment of the lithosphere that evolved separately from adjacent terranes. *Provinces* are large tracts composed of terranes that were consolidated in major convergent tectonic pulses (Karlstrom and Bowring, 1988, p. 562). As originally defined, the Proterozoic rocks of central Arizona were divided into the Yavapai and Mazatzal provinces. Bowring and Karlstrom (1990) extended the provinces into Utah, Colorado, and New Mexico and recognized a third province, the Mojave. The provinces are progressively younger to the south and east.

The boundaries of these provinces have been shown differently by different researchers, depending on the criteria used to define them. Bowring and Karlstrom (1990) showed the boundary between the Yavapai and Mazatzal provinces as extending northeastward from central Arizona to just south of the Four Corners, then along the northern side of the Needle Mountains, and northeastward across Colorado. Condie (1992, p. 448) showed a somewhat different boundary between the Yavapai and Mazatzal provinces, based primarily on the age and composition of the rocks in the respective provinces and a gravity anomaly that extends northeastward from Arizona into New Mexico. His boundary trends northeastward through northwestern New Mexico, well south of the study area (fig. 1), placing the entire Paradox Basin within the Yavapai province.

Karlstrom and Daniel (1993) reconciled the different interpretations of province boundaries by drawing a distinction between Proterozoic orogenic belts and crustal



LIST OF WELLS

185
Reynolds Mining Corp.
Sindbad Unit No. 1
Sec. 26, T. 22 S., R. 12 E.

190
Kerr McGee
TP Utah 27 No. 1
Sec. 7, T. 23 S., R. 13 E.

200
Shell Oil
Gruvers Mesa
Sec. 19, T. 24 S., R. 16 E.

210
Superior Oil
Bow Knot Unit No. 43-20
Sec. 20, T. 25 S., R. 171/2 E.

227
Pan American
Murphy Range Unit No. 1
Sec. 12, T. 28 S., R. 18 E.

237
Humble Oil
Rustler Dome No. 1
Sec. 4, T. 29 S., R. 20 E.

250
Chorney Oil Co.
Hart Point Federal No. 1-22
Sec. 22, T. 31 S., R. 22 E.

263
Gulf Oil
Coal Bed Canyon Unit No. 2
Sec. 20, T. 35 S., R. 26 E.

84
Gulf Oil
Fulks No. 1
Sec. 27, T. 37 N., R. 17 W.

73
Skelly Oil
Lloyd Benton No. 1
Sec. 15, T. 33 N., R. 13 W.

provinces. The boundary between the Yavapai and Mazatzal orogens, based on the age of deformation, is that defined by Bowring and Karlstrom (1990); however, the boundary between the Yavapai and Mazatzal crustal provinces, based on age, composition of rocks, and gravity and magnetic anomalies, corresponds to the boundary shown by Condie (1992).

The gneiss complex had undergone one interval of metamorphism and was experiencing another period of folding when bodies of granitic igneous rocks were intruded into the complex, probably as a result of partial melting associated with subduction (Condie, 1982; Dickinson, 1989). Igneous intrusions were emplaced into the gneiss complex during three main episodes of activity, one about 1,730–1,700 Ma, another about 1,435–1,400 Ma, and a third about 1,000 Ma (Tweto, 1987, p. A22; Gonzales and others, 1994, p. 49). The 1,730–1,700-Ma group is called the Routt Plutonic Suite, the 1,435–1,400-Ma group is called the Berthoud Plutonic Suite, and the 1,000-Ma rocks are called rocks of the Pikes Peak batholith. In southwestern Colorado only the Routt and Berthoud Suites are present. The Routt Plutonic Suite is Early Proterozoic, and the Berthoud is Middle Proterozoic (Tweto, 1987).

Rocks of the Routt Plutonic Suite range compositionally from gabbro to granite but are mainly granodiorite to quartz monzonite. In the study area, the Tenmile and Bakers Bridge Granites, north of Durango, Colo., are in this suite. Rocks of this suite also crop out in Unaweep Canyon, northeast of Gateway, Colo. Reed and others (*in* Van Schmus and others, 1993, p. 217) suggested that differences in age, evolution, and tectonic style of the intrusive rocks may make their grouping into one unit inappropriate. Gonzales and others (1994) distinguished deformed granitoids (Tenmile Granite) from slightly younger undeformed granitoids (Bakers Bridge Granite).

The Berthoud Plutonic Suite rocks are mainly granite and quartz monzonite but include rocks of other compositions. In southwestern Colorado, the Vernal Mesa Quartz Monzonite, Eolus and Trimble Granites, and Electra Lake Gabbro are part of this suite. The Vernal Mesa Quartz Monzonite is exposed at the Black Canyon of the Gunnison and in scattered outcrops along the southwestern margin of

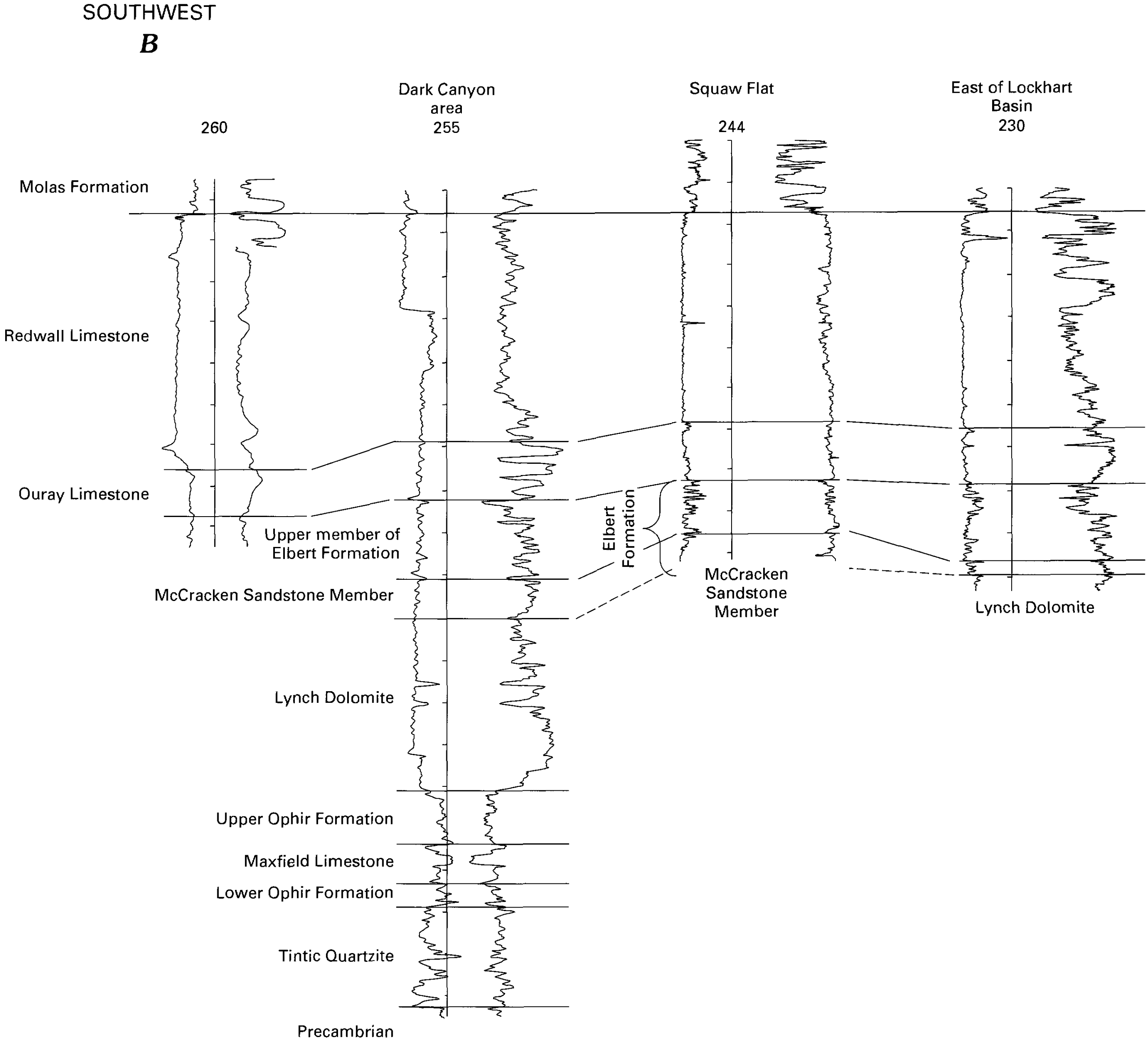
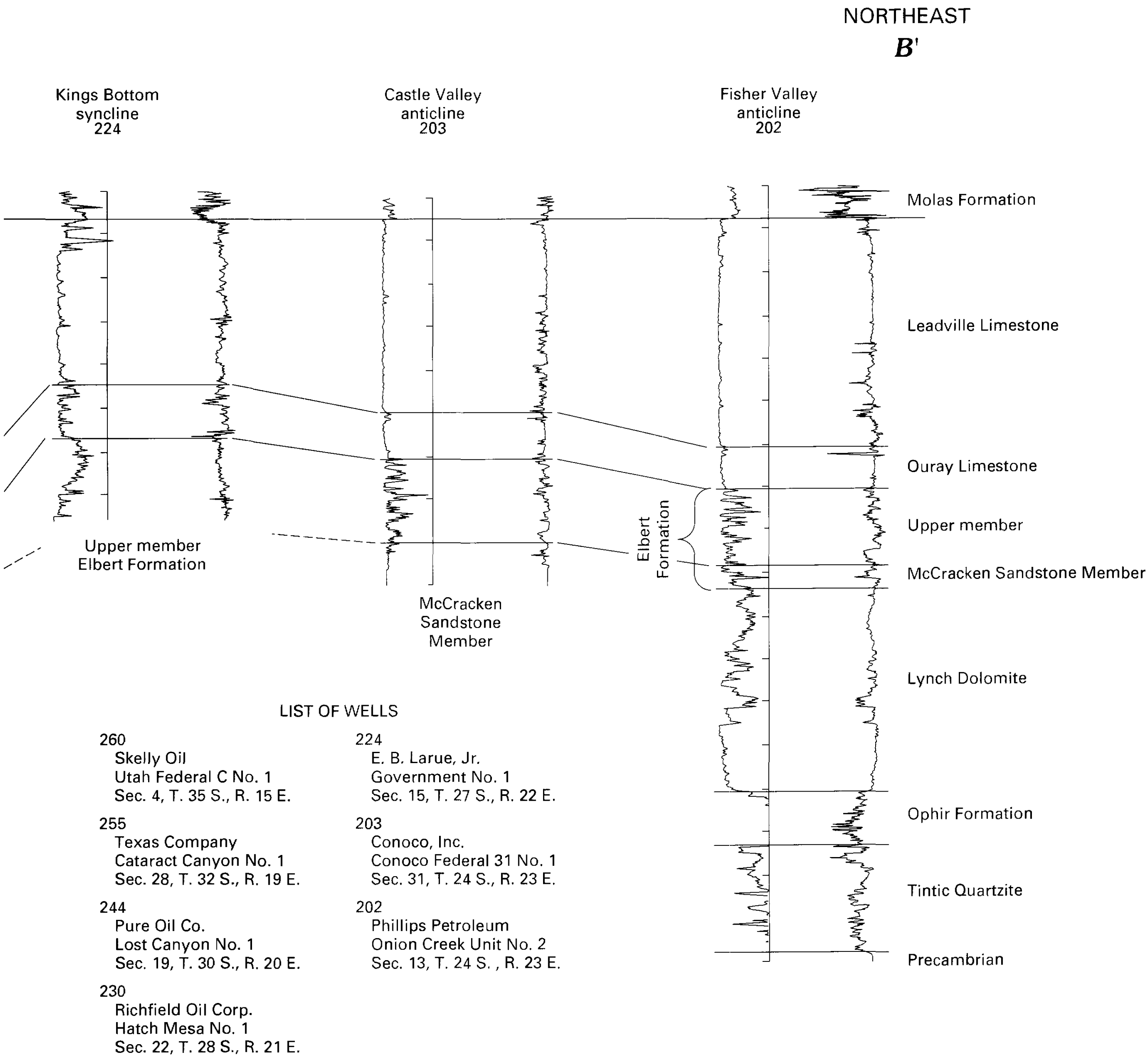


Figure 7 (above and facing page). Cross section of pre-Pennsylvanian units parallel to the Colorado River from south of Hite to northeast of Moab, Utah. Numbers above the well logs correspond to those on plate 1 and in appendix 1. All logs are gamma ray-neutron, except for number 260, which is spontaneous-potential and resistivity. Vertical ticks are every 100 ft; horizontal scale is variable. Line of section shown on plate 1.

the Uncompahgre Plateau. The other igneous bodies are in the Needle Mountains north of Durango, Colo. The Trimble Granite may be as young as 1,350 Ma (Gonzales and others, 1994).

Another group of Early to Middle Proterozoic rocks in southwestern Colorado comprises layered metasedimentary rocks that are younger than the gneiss complex but older than the Middle Proterozoic Eolus Granite. These rocks include the Uncompahgre Formation and the possibly time equivalent Vallecito Conglomerate. The Uncompahgre is composed of quartzite, slate, and phyllite, whereas the Vallecito is a quartzite pebble to boulder conglomerate. Structural relations between these formations and other Proterozoic rocks are complex, but the rocks are thought to be younger than 1,695 Ma and older than 1,435 Ma (Tweto, 1987; Tewksbury, 1989). The younger age is constrained by the intrusive contact of the 1,435-Ma Eolis Granite with the Uncompahgre (Barker, 1969; Tewksbury, 1985). Condie (1981) showed the Uncompahgre as equivalent in age to the Uinta Mountain Group, but the Uinta Mountain Group is now thought to be considerably younger, about 900–800 Ma (Elston and others, p. 470, *in* Link and others, 1993).

Earlier workers (for instance, Barker, 1969) considered the contact between the Uncompahgre and the underlying



Irving Formation and Twilight Gneiss to be an unconformity, but Tewksbury (1985) interpreted the contact as a fault produced by southward movement of an allochthonous block. Harris and others (1987), however, again interpreted the contact as an erosional unconformity. They concluded that the mylonized rock at the contact was a result of north-directed compression that folded the Uncompahgre into the older rocks, essentially in place. This north-directed compression is probably the result of a 1,650–1,600-Ma period of convergent tectonism described by Bowring and Karlstrom (1990). The Uncompahgre itself could be a product of uplift and erosion related to the accretionary process. Van Schmus and others (1993, p. 280) considered the Uncompahgre to be the result of sedimentation caused by rapid uplift and erosion of accreted blocks following emplacement of the 1,730–1,700-Ma plutons. Subsequent metamorphism and folding of the Uncompahgre was interpreted to have occurred at about 1,650 Ma, during formation of what Van Schmus and others (1993, p. 276) termed the "Outer Tectonic belt."

Rocks just to the south of the study area on the Defiance Plateau are also very diverse, ranging from quartzite in Bonito Canyon, near Ft. Defiance, Ariz. (Thaden, 1989), to granite and metasedimentary and metavolcanic rocks near Hunters Point (Fitzsimmons, 1963; Condon, 1986). Although no radiometric dates are available for the Precambrian rocks in this area, Condon (1986) and Thaden (1989) classified the rocks as Early Proterozoic.

The age of the quartzite at Bonito Canyon is somewhat problematic. One possibility is that it is an equivalent of the Uncompahgre Formation, making it 1,695–1,435 Ma in age (Early to Middle Proterozoic). Another possibility is that it is

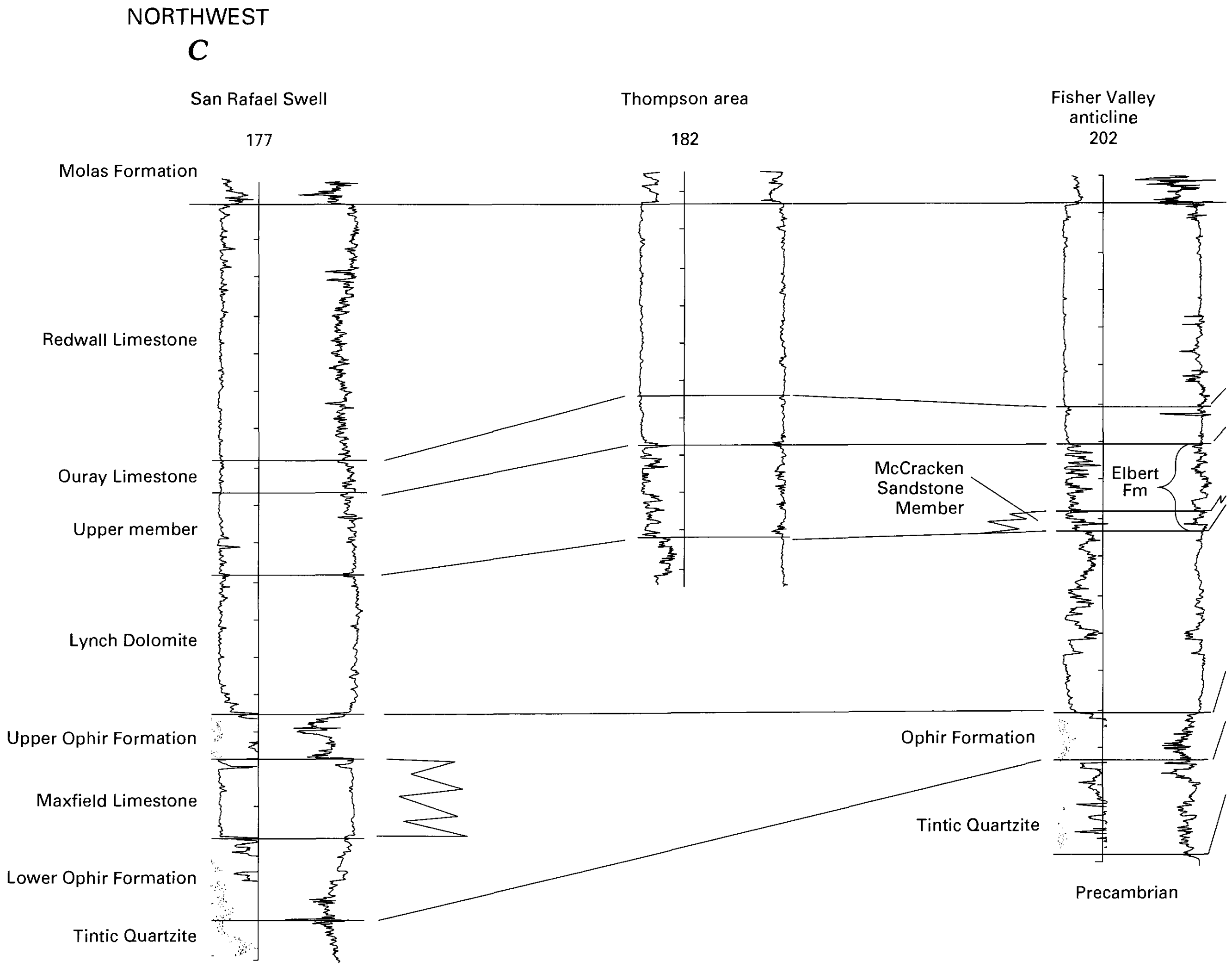


Figure 8 (above and facing page). Cross section of pre-Pennsylvanian units from the San Rafael Swell, Utah, southeastward along the northern margin of the Paradox Basin. Numbers above the well logs correspond to those on plate 1 and in appendix 1. All logs are gamma ray-neutron. Vertical ticks are every 100 ft; horizontal scale is variable. Line of section shown on plate 1.

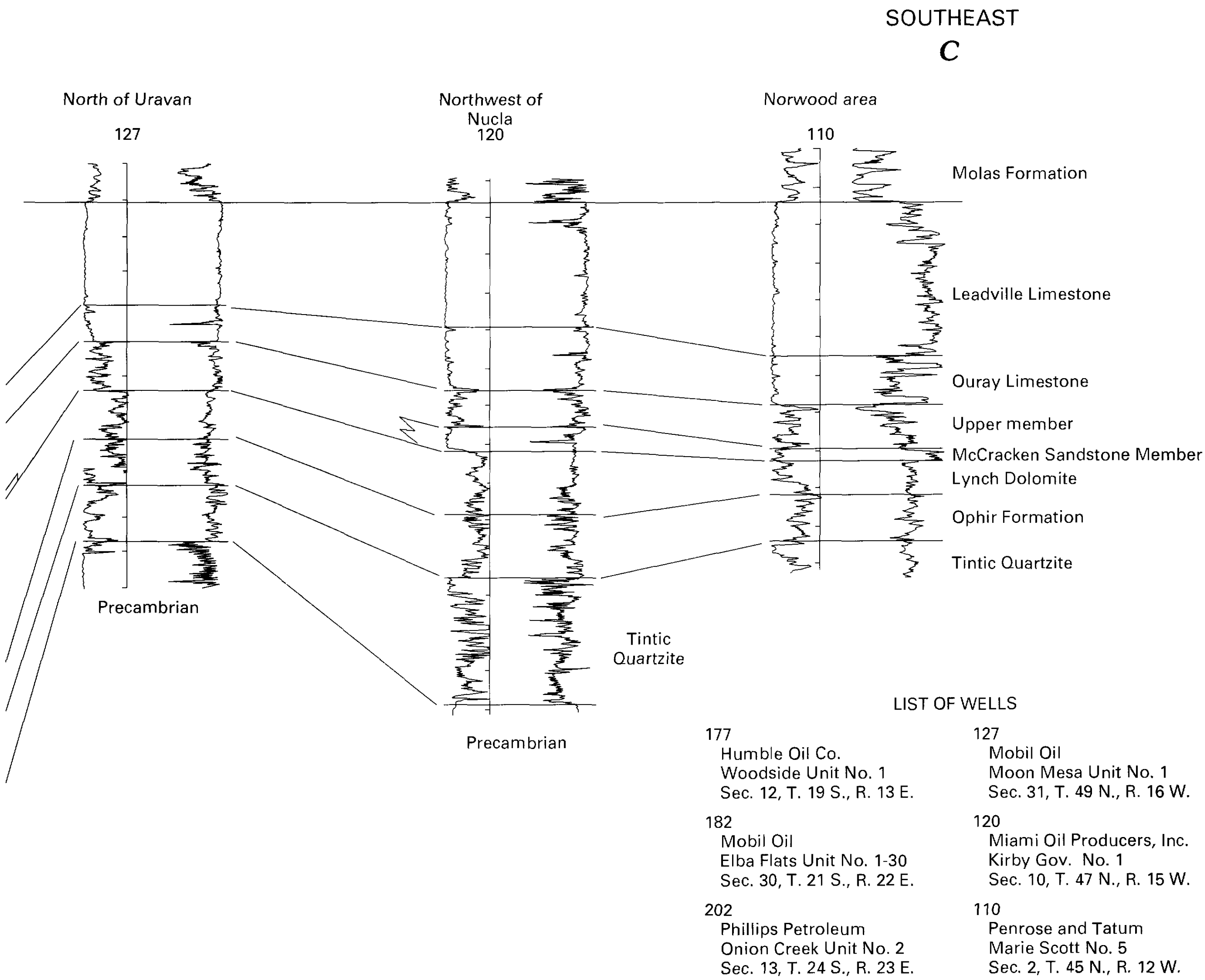
much younger and is equivalent to part of the Grand Canyon Supergroup, which ranges in age from 1,250 to 800 Ma (Elston, 1989; Elston, p. 523, *in* Link and others, 1993) and is composed of the older Unkar Group, Nankoweap Formation, and Chuar Group. Condie (1981) included the Bonito Canyon area in a group of Middle Proterozoic supracrustal rocks 1,200–1,000 Ma in age. Rauzi (1990, p. 25) suggested that, during deposition of the upper part of the Grand Canyon Supergroup, the Four Corners area and Monument upwarp were structurally high and formed the eastern side of the basin in which the Chuar Group was deposited. If Rauzi's proposed eastern boundary of the Chuar is correct, and the quartzite is younger than the Uncompahgre Formation, then the quartzite at Bonito Canyon is most likely equivalent to some part of the Middle Proterozoic Unkar Group.

The granite, metavolcanic rocks, and metasedimentary rocks at Hunters Point may well be Early Proterozoic, equivalent to the Vishnu Schist of the Grand Canyon or to the gneiss complex of southwestern Colorado. The lithologies at Hunters Point are similar to those in the other areas where Early Proterozoic rocks are present. This area along the Arizona–New Mexico State line is at the southern edge of the Inner Accretionary belt of Van Schmus and others (1993, p. 275) and is at the southern edge of the Yavapai crustal province of Condie (1992) and Karlstrom and Daniel (1993).

SUBSURFACE PROTEROZOIC ROCKS

Oil and gas wells in the Paradox Basin and surrounding areas are the sources of a few samples of basement rocks. Previous studies of these samples include those by Edwards (1966) and Tweto (1987) in Colorado, Foster and Stipp (1961) and Fitzsimmons (1963) in New Mexico, and Rauzi (1990) in Arizona and southern Utah.

For the present study a map (pl. 3) was prepared that summarizes the lithology of basement rocks in the



subsurface of the Paradox Basin and adjacent areas. The reports cited above were used to classify some of the samples, and lithologic logs from the American Stratigraphic Company (AMSTRAT) were used to determine the basement lithology in many wells. Cuttings for some of the wells were examined by me from samples stored at the USGS Core Research Center. For some wells that reached basement, no samples or descriptions are available. These holes were still plotted on the map and were used for structure and isopach maps. Appendix 1 summarizes the data.

Various symbols used on the map indicate different lithologic classes: B, basic igneous; G, granite; GN, gneiss and schist; M, metasediment; MV, metavolcanic; and U, unknown. Rock types included in the basic igneous class (B) include samples identified as olivine gabbro or diorite. Rocks included in the granite class (G) include granite, quartz monzonite, granodiorite, and quartz diorite. The gneiss and schist class (GN) includes both gneisses and schists with various modifiers (for example biotite gneiss, muscovite schist), a sample identified as "amphibolite and gneiss," and a sample only identified as "metamorphic" but whose description seems to indicate a crystalline metamorphic rock type. The class labeled metasediment (M) includes those samples that probably have a sedimentary origin, including quartzite and phyllite, and that have not undergone significant metamorphism. Many of the AMSTRAT logs provide only sketchy descriptions of some samples, but comparison of those descriptions with samples examined by myself, led me to classify these samples as metasediment (M). Only a few samples were identified as metavolcanic (MV), although some of the gneisses and schists probably also have a volcanic origin. It is possible that some samples classified as quartzite may, in fact, be volcaniclastic. Many of the wells reached Precambrian, but either they were not logged by AMSTRAT, the logs were not available to me, or the samples were not available for examination. These wells are labeled as unknown (U). In some cases, examination of the cuttings led me to classify the sample differently than the AMSTRAT well logger. Appendix 1 shows the classifications of both AMSTRAT and the author.

Holes reaching Precambrian within the Paradox Basin proper are few and are widely scattered (pl. 3). The lithology

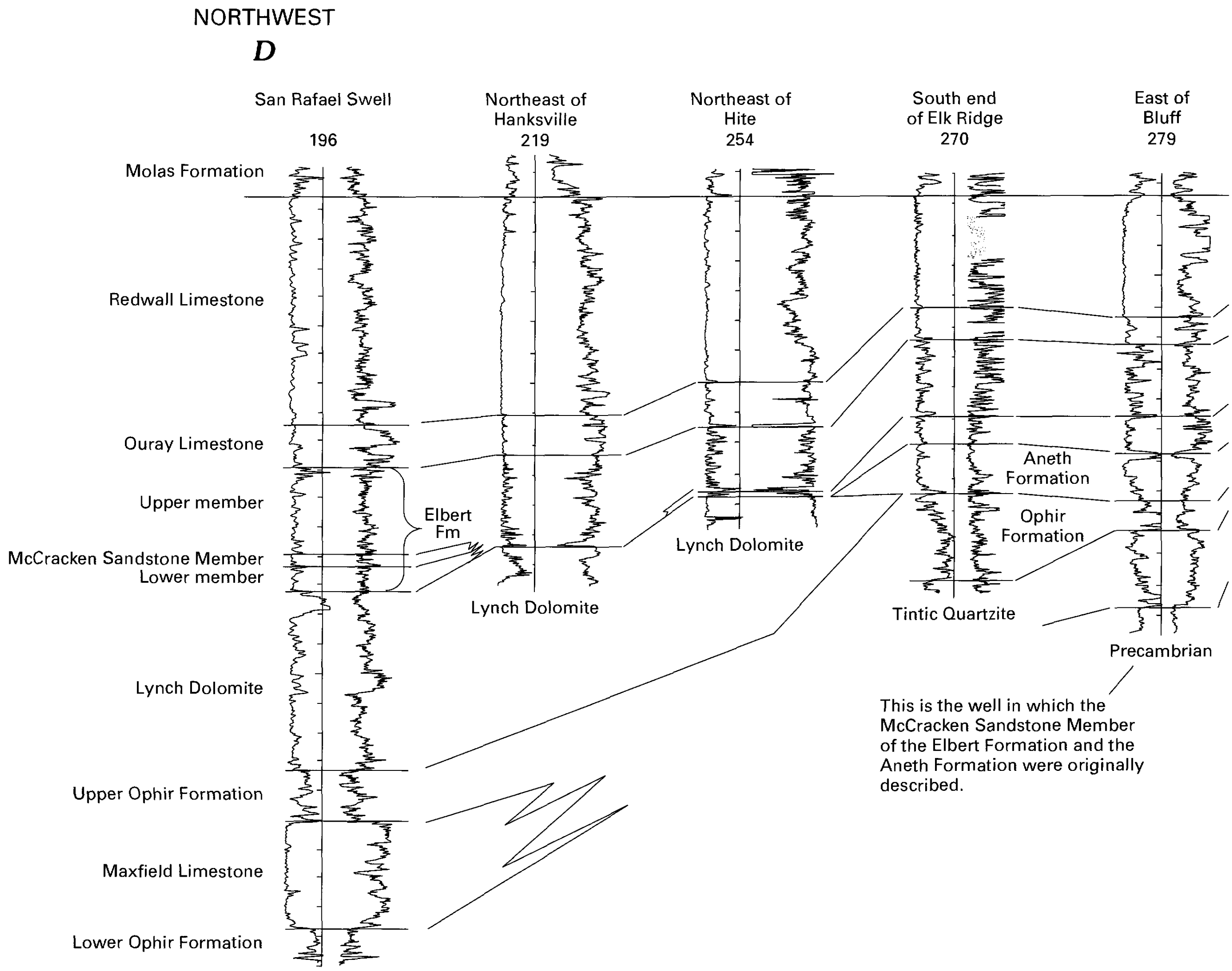


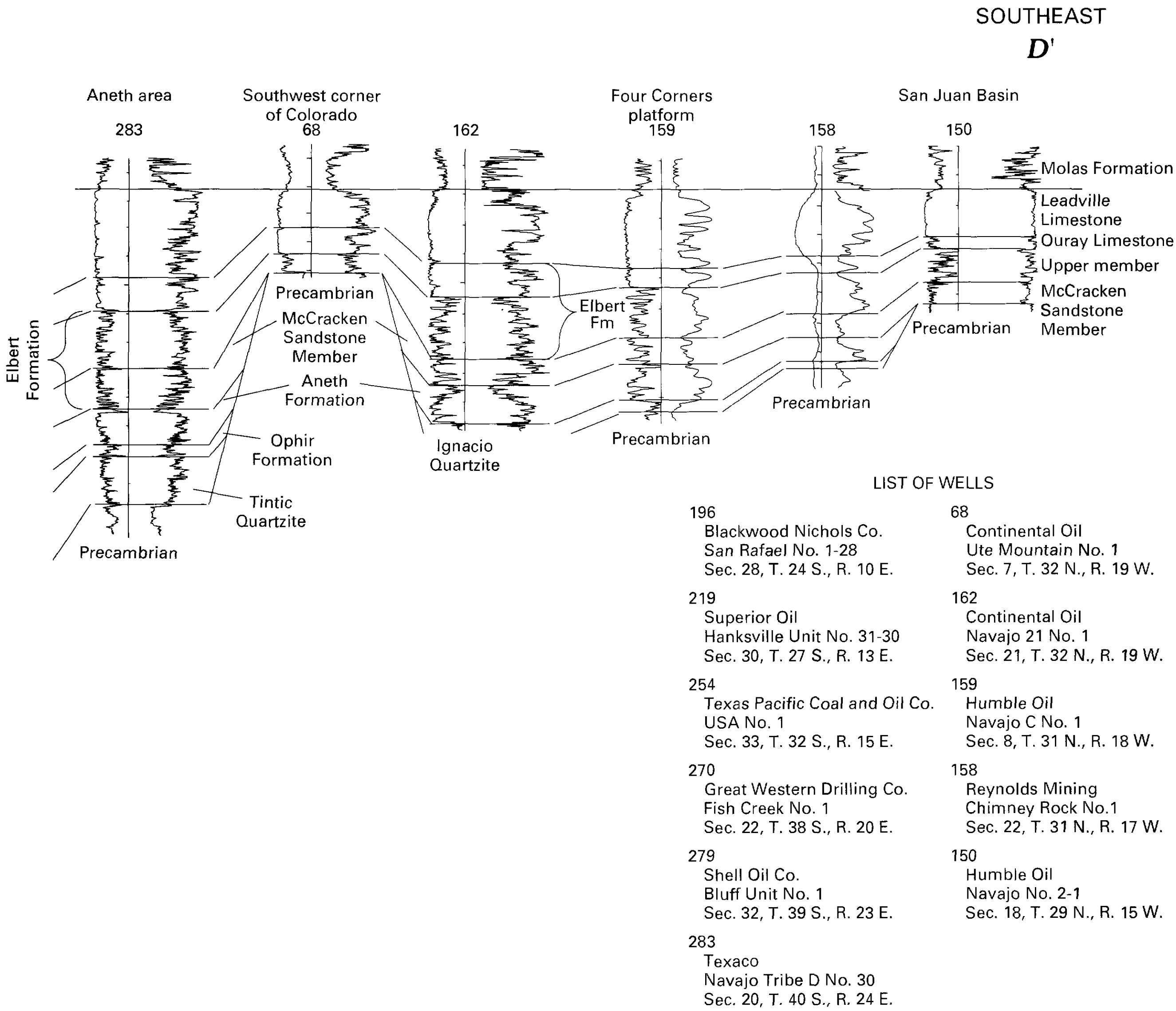
Figure 9 (above and facing page). Cross section of pre-Pennsylvanian units from the San Rafael Swell, Uath, to the San Juan Basin, New Mexico, along the southern margin of the Paradox Basin. Numbers above the well logs correspond to those on plate 1 and in appendix 1. All logs are gamma ray-neutron, except for number 158, which is spontaneous-potential and resistivity. Vertical ticks are every 100 ft; horizontal scale is variable. Line of section shown on plate 1.

of holes in the eastern part of the basin is mainly granite, whereas that of wells in the southwestern part is metasedimentary. Northwest of the basin, on the San Rafael Swell and wrapping around the northern end of the basin, the lithology is mainly granite. Granite is also a dominant lithology east of the basin in Colorado. Rock types in New Mexico include granite and metasedimentary and metavolcanic rocks. Metasedimentary rocks dominate in some areas of northeastern Arizona; however, one area is composed mostly of granite.

Relations in the subsurface in parts of northeastern Arizona and northwestern New Mexico are similar to relations exposed in the Needle Mountains of southwestern Colorado. A crystalline basement of older gneiss and schist most likely was intruded by granite during the 1,730–1,700-Ma or 1,435–1,400-Ma episode of emplacement.

The origin of quartzite in the cluster of holes in the northeastern corner of Arizona is uncertain. Its composition suggests that it is younger than the gneiss complex of southwestern Colorado. An alternative is that the quartzite is an eastern facies of the Unkar or Chuar Groups (Middle to Late Proterozoic) of the Grand Canyon. As previously noted, however, Rauzi (1990) interpreted the eastern edge of the Chuar depositional basin to be farther west than this group of holes. The older Unkar Group (Middle Proterozoic; Elston, 1989) contains considerable amounts of quartzite, suggesting a possible correlation. Bayley and Muelberger (1968) and Condie (1981) included this area in rocks equivalent to the Apache Group (Middle Proterozoic) of central Arizona.

Overall, the lack of data does not allow for a detailed description of the distribution of Proterozoic lithologic types within the Paradox Basin. All of the basin was included in the Yavapai crustal province of Condie (1992) and Karlstrom and Daniel (1993) or the Inner Accretionary belt of Van Schmus and others (1993). As such, it is most likely



composed primarily of biotitic gneiss and schist and is intruded by 1,730–1,700-Ma and 1,435–1,400-Ma plutonic rocks of various compositions. As noted above, the Mineral Mountains, west of the Paradox Basin, are of a similar age and lithology to the rocks of the biotitic gneiss complex of central Colorado (Aleinikoff and others, 1986), suggesting lithologic continuity between those two areas. Although the possibility cannot be ruled out, it is unlikely that there are large areas of quartzite corresponding to the Uncompahgre Formation of the Needle Mountains in the subsurface of the Paradox Basin.

Recently, interest has been expressed in determining the possible occurrence of rocks equivalent to the Chuar Group in the Paradox Basin (Anonymous, 1990). This unit may have potential as a source rock for oil (Reynolds and others, 1988). The Chuar was identified by AMSTRAT in a well west of the Paradox Basin (Tidewater Oil Co., Utah Federal A No. 1, sec. 34, T. 42 S., R. 2 W., Kane Co., Utah), and I examined cuttings from this well. I then examined cuttings from many other wells in southeastern Utah and northeastern Arizona in order to compare them with those from the known Chuar in the Tidewater well. The Tidewater well is far enough west of the study area that it is not shown on plate 1 or listed in appendix 1.

In the Tidewater well the cuttings of Chuar are mostly unmetamorphosed dark-gray to gray-green silty shale, reddish silty shale, gray siltstone, and minor white quartzite. In wells to the east, similar lithologies were found; however, the rocks are slightly more metamorphosed than those in the Tidewater well. A common lithology in wells in southeastern Utah and northeastern Arizona is light- to dark-green and purple phyllite and gray quartzite. In some wells green phyllite and quartzite predominate, whereas in other wells purple phyllite is more common. None of the cuttings examined from northeastern Arizona or southeastern Utah were as unmetamorphosed as those from the Chuar Group in the Tidewater well, although there was some lithologic similarity. Many of these samples that were classified as quartzite by AMSTRAT were not clean orthoquartzites but rather were of a somewhat heterogeneous lithology.

I also examined cuttings from wells in the northwestern part of the basin, northeast and southeast of the San Rafael Swell, that were shown to contain Chuar equivalents (Anonymous, 1990). In the hole northeast of the swell (number 171, appendix 1, pl. 1), the lithology of the Precambrian is a quartz-biotite gneiss, similar to Precambrian rocks in parts of the Uncompahgre Plateau. In the holes southeast of the swell, some samples are similar in many respects to the Chuar in the Tidewater hole. In the Texaco Temple Springs Unit No. 2 well (number 208, appendix 1, pl. 1), the lithology of the Precambrian is a medium-brown to light greenish-gray phyllite and quartzite. In the Texaco Temple Springs Unit No. 1 well (number 207, appendix 1, p. 1), the lithology is a light-greenish-gray quartzite and reddish-brown phyllite. The phyllite in this hole is micaceous and slightly foliated; it appears to have undergone slightly more intense metamorphism than in the other Texaco well.

The lithology of the Precambrian in these two wells, as well as that in some other parts of southeastern Utah and northeastern Arizona, suggests that there is an area of little to moderately metamorphosed metasedimentary rocks. These rocks probably overlie a sequence of older gneiss and schist or granite, but their age and correlation remain unknown.

STRUCTURE OF THE PRECAMBRIAN BASEMENT

A structure contour map of the Precambrian basement (pl. 4) prepared for this study mainly shows the influence of Laramide deformation, but Laramide structures overprint structures at least as old as Pennsylvanian, and probably older. In general, the map shows the same features as the map of the top of the Mississippian (pl. 2). It is much less detailed because of the lack of deep drilling in much of the basin, but it does indicate the depth at which basement rocks are present in many parts of the basin. The San Rafael Swell, Uncompahgre Plateau, Defiance Plateau, and Monument upwarp positive areas are represented on this map. The southern edge of the Uinta Basin and the northwestern edge of the San Juan Basin are also evident, on the north and southeast sides of the map, respectively.

There is approximately 20,000 ft of structural relief from the top of the basement on the Uncompahgre Plateau to the deepest parts of the basin. Seismic studies by A.C. Huffman, Jr., and D.J. Taylor (oral commun., 1993) indicate that there may be even more relief along part of the northeastern margin of the basin. It should be noted that the trend of the Uncompahgre Plateau does not follow a basement lithologic break but rather cuts across lithologic trends.

SEDIMENTARY BASIN FILL

A map not directly involving the Precambrian, but tied to Precambrian data, is shown as plate 5. This map is an isopach map of the present-day sedimentary fill in the Paradox Basin and surrounding areas. The interval from the current ground surface or the Kelly bushing at the well head to the top of the Precambrian was contoured to produce the map. Because formations at the surface are different in different areas, depending on local structure, this map does not show the thickness of strata from any one formation to basement. The map illustrates the very thick basin fill in the northeastern part of the Paradox Basin, as well as thick sedimentary sequences in the southern Uinta Basin at the northern margin of the map and in the San Juan Basin in the southeastern part of the map. Strata are correspondingly thin over the San Rafael Swell, Uncompahgre and Defiance Plateaus, and Monument upwarp. Within the Paradox Basin, strata thin fairly uniformly from east to west, except in an area just east of Hanksville, Utah, where an anomalously thick sequence is present.

CAMBRIAN ROCKS

A period of nondeposition or erosion, at least 500 m.y. in duration (Dickinson, 1989), separates Precambrian and Cambrian rocks in Arizona. Dickinson (1989) noted that the general concordance of Middle Proterozoic and Middle Cambrian strata attests to the development of a stable cratonic shelf in the late Precambrian. This stable shelf probably also extended northward into the area of the Paradox Basin. Rifting on the western edge of the craton in late Precambrian time led to the development of the Cordilleran miogeocline (Dickinson, 1989), a feature that persisted through the remainder of pre-Mississippian time (fig 4).

An irregular erosion surface separates Proterozoic and Phanerozoic rocks of the Paradox Basin. In most of the basin Precambrian rocks are overlain by Cambrian rocks (fig. 5). Exceptions are on the southwestern side of the Uncompahgre Plateau where Permian and Triassic rocks have been mapped overlying Precambrian rocks; in the subsurface adjacent to the Uncompahgre Plateau Devonian, Mississippian, or Pennsylvanian rocks may directly overlie Precambrian rocks. In southwestern Colorado there are examples of Devonian rocks overlying Precambrian rocks both at the surface and in the subsurface. Several reports show the distribution of Cambrian units in the subsurface of the Paradox Basin and adjacent areas (Cooper, 1955, 1960; Lochman-Balk, 1956, 1972; Baars and Knight, 1957; Baars, 1958; Loleit, 1963; Lessentine, 1965; Stevenson and Baars, 1977; Franczyk, 1991; Condon, 1992; Poole and others, 1992). Cambrian rocks in the Paradox Basin form an eastward-thinning clastic and carbonate wedge (pl. 6). East-central Utah is in somewhat of a transition zone with respect to nomenclature used for Cambrian strata. Because the Paradox Basin is primarily in Utah and Colorado, nomenclature from those two States is used in most cases. Reference to names used in the Grand Canyon is made herein to establish the broad correlations to that area.

Lochman-Balk (1956) and Loleit (1963) argued for a different approach, in which a combination of Grand Canyon and central Utah names are used in the Paradox Basin. The argument for this approach is that the Grand Canyon sequence and Paradox Basin rocks were deposited on a stable shelf, whereas the Cambrian rocks of central Utah were deposited on the edge of a deep miogeocline. Lochman-Balk (1972) showed, however, that Cambrian lithofacies extend uninterrupted from the Grand Canyon to central Utah; local names came into use more because of the distance between areas and because studies were done at different times than for geological reasons.

A basal clastic unit is known as the Tintic Quartzite in central Utah, as the Ignacio Quartzite in southwestern Colorado, and as the Tapeats Sandstone in northern Arizona. An overlying shale in the western part of the Paradox Basin is called the Ophir Formation (or Shale) in central Utah and the Bright Angel Shale in the Grand Canyon. This unit extends eastward into Colorado in the northern part of the Paradox Basin. A carbonate unit above the Ophir and Bright Angel is the Maxfield Limestone in central Utah and the Muav Limestone in the Grand Canyon. The uppermost Cambrian unit in the basin is called the Lynch Dolomite in Utah; correlative rocks are unnamed in the Grand Canyon area. The Lynch also extends eastward into the Colorado part of the basin. Contacts between Cambrian units are conformable.

TINTIC QUARTZITE AND IGNACIO QUARTZITE

The Tintic Quartzite is present in most of eastern Utah (Lochman-Balk, 1956, 1972; Hintze, 1988), although it is not exposed anywhere in the Paradox Basin. The Tintic is exposed to the northwest of the Paradox Basin in the East Tintic Mountains where it was described by Morris and Lovering (1961, p. 13). In that area it contains a basal quartzite conglomerate that overlies the Late Proterozoic Big Cottonwood Formation. The lower 300 ft of the Tintic is dominated by conglomerate, and conglomerate is common in the lower 650 ft. Conglomerate clasts are rounded pebbles 1–1.5 in. in diameter that consist mainly of quartzite but also include milky white quartz and phyllite. Most of the rest of the formation consists of light-colored, fine- to medium-grained, crossbedded quartzite and thin, gray-green shale beds in its upper part. A tabular mass of basic igneous rock, about 40 ft thick and 975 ft above the base of the Tintic, was interpreted as a basalt flow (Morris and Lovering, 1961, p. 16). The Tintic Quartzite in this area is 2,300–2,800 ft thick and is overlain gradationally by the Ophir Formation.

The Tintic present a little northeast of the East Tintic Mountains, in the central Wasatch Range, was described by Calkins and Butler (1943) and Anderson (1974). In this area the Tintic is only about 800 ft thick but is similar in other respects to exposures in the East Tintic Mountains. It has a basal quartzite- and quartz-pebble conglomerate, a middle part composed mainly of quartzite, and a few shale beds in its upper part. In this area the basal conglomerate is only about 1 ft thick. Calkins and Butler (1943, p. 10) noted westward-dipping crossbeds in the quartzite.

A lithostratigraphic correlative of the Tintic, the Ignacio Quartzite, is exposed on the southeast side of the Paradox Basin around the flanks of the Needle Mountains of Colorado. The Ignacio was named by Cross (1901) and is described in several atlases of the Needle Mountains area (Cross, Howe, and Ransome, 1905; Cross, Howe, Irving, and Emmons, 1905; Cross and others, 1910). [Note: In Condon (1992) the naming of the Ignacio was inadvertently attributed to Cross, Howe, and Ransome (1905). The Cross (1901) report is considered the first use of the name by the U.S. Geological Survey.] More recently, the Ignacio outcrops have been discussed by Barnes (1954), Baars and Knight (1957), Rhodes and Fisher (1957), Baars (1958, 1966), Baars and See (1968), Baars and Ellingson (1984), and Campbell (1994a, b).

In the Needle Mountains area the Ignacio is a heterogeneous unit that consists of basal quartzite pebble and boulder conglomerate and vein-quartz conglomerate as well as quartzite similar to that to the west in central and northern Utah in the Tintic. Additionally it contains significant amounts of siltstone, shale, and dolomite in some places (Baars and See, 1968; Baars and Ellingson, 1984). The quartzite-pebble conglomerate contains rounded clasts, as much as 2.5 ft in diameter, that are mainly of the composition of the underlying or nearby Proterozoic Uncompahgre Formation. The contact between the Ignacio and Precambrian is irregular, and the conglomerate fills in channels at the top of the Precambrian (Cross and Hole, 1910).

The overlying quartzite of the rest of the formation is white, light-gray, and light-purple, fine- to coarse-grained, crossbedded, silicified sandstone. Baars and See (1968, p. 337) noted that the lithology of the Ignacio changes laterally from quartzite to siltstone in short distances and that the unit locally contains green, red, brown, or tan, micaceous, sandy shale in its upper part. This shale contains brachiopods (Rhodes and Fisher, 1957; Baars and See, 1968). Thin, dark-colored dolomite beds are associated with the shale in some places. Trace fossils consisting of horizontal tubular structures were observed at the base of the Ignacio near Coal Bank Pass (fig. 10).

The lithology of the Tintic and Ignacio in the subsurface, as revealed by AMSTRAT sample logs, is similar to that described at the outcrop. The units are generally light-colored, coarse-grained to conglomeratic,

Figure 10. Trace fossils within quartzite at the base of the Ignacio Quartzite near Coal Bank Pass. Hammer head is 8 in. long.

silica-cemented sandstone and thin, interbedded, green, gray, and red shale and siltstone beds.

In one well, the lower part of the Ignacio or Tintic is an arkosic conglomerate that contains granite pebbles. This lithology is different from that of the conglomerates of the Needle Mountains area, which consist of quartzite or quartz pebbles. This different lithology can no doubt be attributed to the lithology of the underlying Proterozoic rocks. The presence of arkosic conglomerate in this hole (well 262, appendix 1, pl. 1), in an area bordered by Blanding and Monticello on the west and the Utah-Colorado State line on the east, is significant. It is an indication that either there were large streams capable of carrying coarse detritus from granitic highlands far to the east or the local relief was great enough to shed a wedge of arkose. The lithology of the basement at this hole is granite (appendix 1), and I believe that the arkosic conglomerate has a local source. This hole is near the axis of the Dove Creek anticline and may be another example of relief on the Precambrian surface that was illustrated by Baars (1966) in the Paradox Valley area. The present Dove Creek anticline may be an example of a reactivated Precambrian structure.

In the Fulks No. 1 well (number 84, appendix 1, pl. 1), strata assigned to the Ophir Formation could also have been included in the Ignacio. In this hole the upper part of the Cambrian section consists of thin-bedded, interstratified sandstone, siltstone, shale, and dolomite. This sequence is similar to strata assigned to the Ignacio in the Needle Mountains area by Baars (1966). It was assigned to the Ophir in this report because of its similarity to the Ophir in other wells farther to the west. In the Tidewater well in which the Chuar Group was described previously, the Tintic consists of conglomerate and medium- to coarse-grained sandstone interbedded with thin, green shale partings. The composition of the pebbles in the basal conglomerate is unclear from the AMSTRAT description.

Baars (1966), Baars and See (1968), and Baars and Stevenson (1982) interpreted the quartzite pebble and boulder conglomerate at the base of the Ignacio as talus shed from a Cambrian highland of Uncompahgre Formation rocks. Their interpretation was that, during deposition of the Ignacio, outcrops of the Uncompahgre stood above older Proterozoic rocks, such as the Twilight Gneiss and Irving Formation, as a result of differential erosion. The highland was thought to have contributed coarse clastic material that graded laterally into quartzite, dolomite, and shale in a seaward direction along fault-bounded shorelines (Baars and See, 1968, p. 339, 347).

Campbell (1994a, b) made an important distinction between the quartzite conglomerates and vein-quartz conglomerates that questions the model of talus being shed from fault-bounded basement blocks. Campbell (1994a, b) concluded that the quartzite conglomerates were deposited in proximal braided streams that had local sources and that flowed to the west and southwest. He suggested that the age of the quartzite conglomerates is late Precambrian to early Cambrian. Additional descriptions of the Precambrian-Cambrian contact in the Needle Mountains area are given in appendix 3.

Middleton (1989) summarized environments of deposition of the Tapeats Sandstone in northern Arizona. In that area the Tapeats is primarily a shallow-marine deposit that displays features related to tidal currents. The base of the Tapeats also contains fluvial rocks that were deposited in broad, shallow, braided systems. Lochman-Balk (1956, 1972) showed the configuration of the Cambrian shoreline through time. The shoreline had a generally north to northeast trend and an embayment into western and southwestern Colorado. Depositional environments displayed by the Tapeats Sandstone are very likely represented in the Tintic and Ignacio Quartzites in the subsurface of the Paradox Basin.

The boundary between the Tintic and Ignacio Quartzites is undefined and arbitrary. Both units, and the Tapeats Sandstone of the Grand Canyon area, are mainly transgressive deposits at the base of the Cambrian section. Lochman-Balk (1972) demonstrated the transgressive nature of the Tintic and Ignacio as well as other younger Cambrian units. In the west the Tintic has been dated as Early and Middle Cambrian, whereas in the east, the Ignacio is considered Late Cambrian.

Plate 7 is an isopach map of the Tintic and Ignacio Quartzites. This map differs from the isopach map of all Cambrian units in that the thickest parts are along zones oriented southwest-northeast along a line connecting the Monument upwarp with Naturita, Colo., and along a northern trough that extends through Moab, Utah. To the southeast and east, the Ignacio eventually pinches out (Condon, 1992, p. A14). To the northwest, the Tintic is about 100–170 ft thick on and adjacent to the San Rafael Swell (pl. 7). There is no readily identifiable cause for the increase in thickness of Tintic and Ignacio across the Paradox Basin. Perhaps the thick zone represents a strandline along which shoreface sands accumulated. Detailed analysis of core from this zone is needed to establish the depositional environment. The area in the far southwest corner of Colorado is interesting. In this well the Ignacio is apparently absent because a basement high of Precambrian rocks existed as an island, over which no Cambrian rocks were deposited (fig. 9). This area remained high until Late Devonian time.

OPHIR FORMATION

The Ophir Formation conformably overlies the Tintic Quartzite. The Ophir was first defined in north-central Utah and is exposed in several mountain ranges in that area. In the East Tintic Mountains the Ophir is divided into a lower shale member, a middle limestone member, and an upper shale member (Morris and Lovering, 1961, p. 19). The lower member consists of a sequence of dark-brown to greenish sandstone, interbedded greenish-gray shale, and a dolomite or limestone bed. The middle member is composed of beds of dark bluish-gray limestone interstratified with beds of green to light-bluish-green shale. The upper member is mainly light-greenish-gray shale and lenticular beds of sandstone. Even with the other lithologies present, the Ophir as a whole has the aspect of a shale unit lying between the cross-bedded sandstones of the Tintic Quartzite below and the Cambrian carbonate rocks above. In the East Tintic Mountains the Ophir is 275–430 ft thick (Morris and Lovering, 1961). Trilobites in the lower member of the Ophir establish its origin as marine. The Ophir is also recognized in the central Wasatch Mountains, where it is referred to as the Ophir Shale (Calkins and Butler, 1943; Anderson, 1974). In the Wasatch Mountains the Ophir is divisible into the same three members just described, and it is of comparable thickness.

In the Paradox Basin the Ophir is not exposed at the surface; in the Needle Mountains area the only Cambrian unit, the Ignacio Quartzite, is unconformably overlain by Devonian rocks. Plate 8 shows the combined thickness of the Ophir Formation and the Maxfield Limestone in the basin. In the subsurface the Ophir consists of interlayered thin beds of buff dolomite, buff, gray, and green shale and siltstone, and minor beds of white to gray, fine- to medium-grained sandstone. In the Texaco, Inc. No. 6 Unit well (number 220, appendix 1, pl. 1), the upper part of the Ophir consists of primarily sandstone interbedded with some dolomite and minor limestone. Algal material and oolites were noted in this well. Sample logs note fragments of brachiopods and trilobites in some holes.

Studies of the partly correlative Bright Angel Shale in northern Arizona reveal that most of the Bright Angel was deposited in a subtidal to intertidal environment (Middleton, 1989). Extensive, tabular sandstone bodies were deposited as migrating sand sheets whose tops were modified by storm events. Lenticular, fining-upward sandstone sequences were interpreted as storm deposits. A third type of deposit, characterized by large-scale, planar-tabular crossbeds, was interpreted as migrating sand waves (Middleton, 1989). Comparable environments of deposition are probably present in the Ophir Formation in the subsurface of the Paradox Basin.

When compiling the maps for this report I decided to include the Ophir Formation and Maxfield Limestone together for two reasons. (1) There are only a few wells used for this study in which the Maxfield is present; those wells are mainly on the far western side of the study area near the San Rafael Swell. The holes in which the Maxfield is present are marked with an "M" on plate 8. (2) On the geophysical logs the Maxfield Limestone is a carbonate unit that is overlain by a shale having a log response similar to that of the Ophir Formation (figs. 6–9). The Maxfield thus appears as an eastward-thinning carbonate rock encased within shale. This relationship was illustrated diagrammatically by Lochman-Balk (1956).

The present study differs from Lochman-Balk (1956) in that I consider the upper shale unit, above the Maxfield, as a tongue of the Ophir Formation. Lochman-Balk (1956), in contrast, assigned the upper shale to the Maxfield or to the Muav Limestone in southernmost Utah. She attributed the upper shale to regression at the end of the Middle Cambrian. Parker (1961, p. 62) also included the upper shale bed in the Maxfield. He thought that the upper shale and limestone of the Maxfield pinches out eastward and that the shale of the Ophir continues beyond that pinchout. My interpretation is that the limestone of the Maxfield pinches out and the upper and lower Ophir shales merge to the east.

Plate 8 and figures 6–9 show that the Ophir Formation extends eastward across much of the northern and central Paradox Basin. On the northeastern side of the basin the Ophir underlies other shales assigned to the Lynch Dolomite (fig. 8). This is the only area in which no carbonate unit separates the two shales, as is the case farther to the west (figs. 6, 8, 9). In the present study the entire shale unit was originally assigned only to the Ophir, but the resulting thickness is unrealistic. If the whole unit were assigned to the Ophir, it would be more than 300 ft thick in one hole and more than 250 ft thick in several others. Considering the overall thinning to the east that the Cambrian in general exhibits, it is unlikely that the Ophir thickens in that direction. Moreover, the geophysical logs show that the upper part of this unit is quite similar to the shale at the top of the Lynch and that the lower part has a log response similar to that of typical Ophir. As mapped for this report, the combined Ophir and Maxfield thin regularly to the east and an eastward-extending tongue is present in the Slick Rock–Naturita area. This distribution pattern is similar to that for the underlying Tintic and Ignacio Quartzites.

NOTE ON CAMBRIAN NOMENCLATURE

The nomenclature of Cambrian units above the Ophir Formation in central Utah is complex. A series of Middle and Upper Cambrian formations was described and named in the Tintic district, southwest of Provo, Utah, by Loughlin (*in* Lindgren and Loughlin, 1919). These include the Teutonic Limestone, Dagmar Dolomite, Herkimer Limestone, Bluebird Dolomite, Cole Canyon Dolomite, and Opex Formation. Later, Gilluly (1932) introduced a new set of names, the Hartmann Limestone, Bowman Limestone, and Lynch Dolomite, for essentially the same series of beds in the Ophir district, northwest of Tintic. Gilluly cited certain lithologic differences and the distance, "between districts so widely separated (30 miles)," as reasons for not using the older terms. Calkins and Butler (1943) applied the name Maxfield Limestone to beds overlying the Ophir in the Wasatch Mountains, northeast of the Ophir and Tintic districts. The Maxfield is Middle Cambrian and is overlain unconformably by Devonian rocks and is therefore equivalent to only part of the Cambrian sections at Ophir and Tintic. Morris and Lovering (1961) used the names established by Loughlin (*in* Lindgren and Loughlin, 1919) in their study of the East Tintic district.

Based solely on precedence of names and proximity to the Paradox Basin, it would seem that the names of Loughlin (*in* Lindgren and Loughlin, 1919) would have been used in the basin. Instead, the names Hartmann Limestone, Bowman Limestone, and Lynch Dolomite were used by Di Giambattista (1952) and Cooper (1955) for strata in southeastern Utah. Conversely, Lochman-Balk (1956, 1972) showed the Maxfield as an eastward-extending equivalent of the Hartmann and Bowman and used the Maxfield and Lynch in the northern Paradox Basin. Parker (1961) also used the terms Maxfield and Lynch, as did several unidentified geologists who compiled the AMSTRAT lithologic sample logs in various parts of the basin. Hintze (1988, p. 180) used the term "Maxfield" Limestone and "Lynch" Dolomite, undivided, for the San Rafael Swell area. Because of this prior common usage, the terms used for this report are the Maxfield Limestone and Lynch Dolomite for Cambrian stratigraphic units above the Ophir Formation in the Paradox Basin.

MAXFIELD LIMESTONE

The Maxfield Limestone was described in detail by Calkins and Butler (1943, p. 14) for exposures of the unit in the central Wasatch Mountains. In that area the unit is approximately 570 ft thick and consists of limestone, dolomite, and minor shale. Calkins and Butler (1943) divided the Maxfield into several informal members on the basis of the percentage of dolomite in the section. The Maxfield was interpreted as a marine deposit on the basis of its fossil content.

In northern Arizona the Muav Limestone is a partial correlative of the Maxfield. The Muav is characterized by heterogeneous environments of deposition ranging from outer shelf, subtidal carbonate sheets to intertidal and supratidal carbonate rocks and mudstone (Middleton, 1989). Some of the mudstone contains cryptalgal laminations and was probably deposited on tidal flats.

The Maxfield thins eastward from central Utah and is present only on the far west side of the Paradox Basin. Figures 6–9 show log responses of the Maxfield in a few holes, mainly west of the Green and Colorado Rivers. There are too few wells that reached the Maxfield to accurately map its pinchout to the east. In the Texas Company Cataract Canyon No. 1 well (number 255, appendix 1, pl. 1, fig. 7), the Maxfield is a thin carbonate unit encased within shale assigned to the Ophir. This well is the easternmost in which Maxfield was identified in this study. As noted previously, Lochman-Balk (1956) and Parker (1961) included the upper shale in the Maxfield. Using their definition, the Maxfield would have extended eastward into Colorado (fig. 8, pl. 9). As recognized in this report, the Maxfield Limestone probably pinches out west of the Monument upwarp and west of the Colorado River above its confluence with the Green River.

In the few wells where the Maxfield is described on sample logs, it is composed of interbedded brown to gray limestone, brown dolomite, and green to dark-gray shale and siltstone. Beds of dolomite and limestone are as thick as 20 ft but are commonly 10 ft thick or less.

LYNCH DOLOMITE

The Lynch Dolomite, including a shale unit at the top of the formation, is not exposed at the surface in the Paradox Basin. The Lynch was first defined and described by Gilluly (1932) in the Ophir district of central Utah. In that area the Lynch is composed of massive gray dolomite about 825–1,000 ft thick. The lower part of the Lynch includes dark-blue limestone with shale partings, and the upper three-fourths contains distinctive dark-gray to black dolomite with short rods of white dolomite scattered throughout. Marine fossils establish the environment of deposition of the Lynch.

An unnamed dolomite sequence overlies the Muav Limestone in northern Arizona and may be equivalent to the Lynch. This sequence contains oolitic grainstone and stromatolites interbedded with other carbonate rocks (Middleton, 1989) and was probably deposited in shallow water.

Figures 6–9 show the geophysical log character of the Lynch in the Paradox Basin, and plate 9 shows its distribution and thickness. In many places there is a distinctive shale unit at the top of the Lynch. This shale was also shown as part of the Lynch by Parker (1961) but was shown as a post-Lynch Cambrian shale by Parker and Roberts (1963, 1966). The shale is commonly included in the Lynch on AMSTRAT sample logs. This shale unit should not be confused with an overlying dolomite and shale that is at the base of the Elbert Formation. The shale of the Elbert lies above the Lynch shale and below the McCracken Sandstone Member of the Elbert, and it has a limited extent in the northwestern part of the basin.

In the subsurface of the Paradox Basin the Lynch consists of tan to cream limestone and dolomite interbedded with minor shale and sandstone. The upper part of the Lynch is composed of sandy dolomitic shale in many places. Sample logs indicate the presence of algal material, oolites, and brachiopods in some holes.

The distribution of the Lynch in the basin is similar to that of the Ophir Formation (pls. 8, 9). As with the older Cambrian units, there is a lack of drill holes in the central part of the basin with which to show the eastward pinchout of the dolomite. The holes marked with an "L" on plate 9 are where dolomite in the Lynch is present and has been reached by drilling but not penetrated completely. The full thickness of the dolomite part of the Lynch was penetrated in the Phillips Petroleum Onion Creek Unit No. 2 well (number 202, appendix 1, pl. 1, fig. 7) and is 475 ft. This well is nearly at the Utah-Colorado State line, indicating that the dolomite extends eastward for some distance; however, most of the wells in Colorado, on the far northeastern side of the basin, contain only the shale unit at the top of the Lynch.

ORDOVICIAN AND SILURIAN ROCKS

There are no known Ordovician or Silurian rocks in the Paradox Basin. Loleit (1963) suggested, on the basis of a questioned fossil identification, that the Ordovician may be represented, but no subsequent report has verified his suggestion. There is no definitive evidence available that indicates whether the Ordovician and Silurian are absent due to erosion or to nondeposition.

Ordovician rocks are present in the western half of Utah, where they are as thick as several thousand feet. Hintze (1988, p. 21) noted that Lower Ordovician rocks are mainly sandy bioclastic limestone that shows evidence of deposition in shallow-water environments. Middle Ordovician rocks there include thick quartz sandstone that may represent regressive deposits. Based on these nearshore facies in western Utah, it is unlikely that either Lower or Middle Ordovician rocks extended as far eastward as the Paradox Basin. Upper Ordovician rocks are the most widely distributed Ordovician deposits in Utah (Hintze, 1988, p. 21). Their lithology is commonly a dark, cherty dolomite that includes corals and brachiopods. This unit is the most likely of any Ordovician unit to have extended eastward to the Paradox Basin, if any did. Upper Ordovician rocks are also present in central Colorado and points east (Poole and others, 1992).

Silurian rocks in Utah are also limited to the western half of the State. The dominant lithology of Silurian rocks is grayish, cherty dolomite (Hintze, 1988, p. 23). Hintze (1988) noted that there is no evidence of nearshore deposits in Silurian rocks of western Utah, suggesting that the unit may have extended farther eastward into the Paradox Basin area.

If there had been any Ordovician or Silurian rocks in the Paradox Basin, they were removed by erosion in pre-Late Devonian time. The extent of tectonism that could have caused such erosion must have been slight because Upper Cambrian and Upper Devonian strata are essentially parallel in outcrops in the Needle Mountains. Stevenson and Baars (1977) identified several northwest-trending horsts and grabens in which Cambrian strata are selectively preserved. Their work may be an indication that local tectonics played a part in removal of Ordovician and Silurian rocks in the Four Corners area.

DEVONIAN ROCKS

Devonian rocks in the Paradox Basin are represented by the Upper Devonian Aneth Formation, Elbert Formation, and Ouray Limestone. No Lower or Middle Devonian rocks are present. The Elbert is divided into the basal McCracken Sandstone Member and an unnamed upper member. In the northwestern corner of the basin, a few wells contain rocks that have the lithology of the upper member but are below the McCracken. This unit, informally labeled as the lower member of the Elbert, is shown in figure 9. Devonian rocks rest unconformably on Cambrian rocks in most places; in some areas Cambrian strata are absent and Devonian rocks rest on Precambrian rocks. Baars (1972) and Poole and others (1992) summarized the Devonian stratigraphy of the Four Corners area.

Plate 10 is an isopach map of all Devonian rocks in the study area. Notable features of the map are a thin area in southwestern Colorado and a thick area in southeastern Utah. The thin area in Colorado is also an area in which Cambrian rocks are absent; the thin Devonian in this area suggests that a structural high may have controlled deposition there. In general, the Devonian thickens gradually northwestward across the basin.

ANETH FORMATION

The Aneth Formation was defined by Knight and Cooper (1955) for a fossiliferous interval of dark- to light-gray and dark-brown dolomite, gray, brown, and black shale, and gray siltstone. Devonian fish plates and scales and plant fragments are present in the unit. Stringers, veins, and inclusions of anhydrite are present in some of the dolomite beds. The unit was described from core from the Shell Oil Co. Bluff Unit No. 1 well (number 279, appendix 1, pl. 1, fig. 9). On sample logs the Aneth is usually easily distinguishable by being above the shaly interval of the Ophir or above the Ignacio Quartzite and below the sandstone of the McCracken Sandstone Member. Sample descriptions of the Aneth commonly describe it as resinous in some intervals. In general, the Aneth is distinctly darker colored than carbonate intervals in the Lynch Dolomite or in the upper member of the Elbert. The Aneth has not been recognized in surface outcrops anywhere.

Plate 11 is an isopach map showing the thickness and distribution of the Aneth, as used in this report. The Aneth is thickest in an elongated oval area stretching from just west of the Monument upwarp east-northeastward to nearly the Utah-Colorado State line. Another relatively thick area is in northwestern New Mexico, just south of the Colorado State line. It is absent in the immediate vicinity of the Four Corners and southward along the crest of the Defiance Plateau (S.M. Condon and A.C. Huffman, Jr., unpublished data).

There has been considerable disagreement in the interpretation of the lateral extent of the Aneth and its relations to the Elbert Formation. Knight and Cooper (1955) originally considered the Aneth to be restricted to the general Four Corners area. Cooper (1955) showed the Aneth as bounded top and bottom by unconformities. Parker (1961) mapped the Aneth throughout the Paradox Basin and considered it to be gradationally overlain by the Elbert. Parker and Roberts (1963, 1966) agreed with the interpretation of Knight and Cooper (1955) and restricted recognition of the Aneth to the Four Corners area but considered it to be gradational with the Elbert Formation. They believed that the Aneth accumulated in local sags or basinal areas. Baars and Campbell (1968) and Baars (1972) also indicated that the Aneth is limited to the Four Corners area and conformably underlies the Elbert. This model of distribution and contact relations has generally been accepted, although in unpublished work, Rocky Mountain Geological Databases, Inc., followed the interpretation of Parker (1961) and correlated the Aneth throughout the basin.

Sandberg and others (1989) indicated that there is probably a disconformity, representing some 10 m.y., separating the Aneth from the Elbert Formation. Based on conodont zonation (Sandberg and others, 1989), the Aneth and, possibly, the McCracken Sandstone Member are separated by a disconformity from the overlying upper member of the Elbert. Because no conodonts have been recovered from the McCracken, it is not known if the disconformity lies between the Aneth and McCracken or between the McCracken and upper member (C.A. Sandberg, oral commun., 1993). Another interpretation is that the missing conodont zones reflect unfavorable environmental conditions during deposition of the McCracken, or that conodonts were not preserved in the McCracken, and the McCracken was deposited during the 10 m.y. represented by the missing zones (K.B. Ketner, written commun., 1994).

Because McCracken-type sands are present in the upper member and the contact between the McCracken and upper member is apparently gradational, I believe that if there is a disconformity it lies between the Aneth and McCracken. The Aneth, as shown on plate 11, is only present in the general Four Corners area. In the northwestern part of the basin, where the McCracken is absent, basal beds of the Elbert consist of light-tan and light-gray dolomite and greenish shale. This lithology is unlike the dark dolomite and shale of the Aneth in the well where it was first described. For this report, correlations of the Aneth were made from log to log from the Bluff Unit No. 1 well (number 279, plate 1, appendix 1) outward radially. Correlations were extended only when I felt confident that adjacent holes had the typical Aneth lithology.

The reason for the Aneth's limited distribution in the Four Corners area is not clear. Sandberg and others (1982, p. 697) interpreted the Aneth as a transgressive deposit that filled drowned valley systems incised into underlying rocks. Underlying Cambrian rocks in this area do not, however, appear to have been eroded any more in this area than elsewhere, (pl. 6), and thus the presence of incised valleys is uncertain. Isopach maps of the Aneth by Stevenson and Baars (1977) and in the present report (pl. 11) suggest a wider distribution of the Aneth than that recognized by Sandberg and others (1982). Perhaps the control points used for plate 6 are too widely spaced to adequately show the configuration of an incised valley system.

The overlying McCracken Sandstone Member and upper member of the Elbert Formation are also relatively thick in this same area (plates 13, 14), suggesting that this was an area of subsidence that persisted through much of the Late Devonian. The cause of this subsidence is not known. The possibility of a disconformity between the Aneth and overlying Elbert Formation may indicate that remnants of Aneth are preserved in grabens or other downwarps in other areas of the basin.

ELBERT FORMATION

The Elbert Formation was named by Cross (1904) for exposures along Elbert Creek, north of Durango, Colo. The Elbert was defined to include a series of calcareous shale, limestone, and quartzite, all of which contain Devonian fish remains. Knight and Cooper (1955) divided the Elbert into the lower McCracken Sandstone Member and an upper unnamed member.

Plate 12 shows the thickness and distribution of the Elbert in the Paradox Basin. The thickness ranges from 73 to 422 ft in the study area. Thickest areas are in the northwestern and southwestern parts of the area, and the thinnest area is in the southwestern corner of Colorado where the upper member directly overlies Precambrian rocks.

McCRACKEN SANDSTONE MEMBER

The McCracken Sandstone Member was also defined and described by Knight and Cooper (1955) from the Bluff Unit No. 1 well in southeastern Utah. As originally described, the McCracken consisted of interbedded light- to dark-greenish-gray, light- to medium-gray, and pinkish, fine- to coarse-grained glauconitic sandstone, white, pink, green, and light-gray to brown argillaceous dolomite, and minor grayish-green shale. In some sample logs the McCracken is a thick sandstone unit with few interbeds of other rock types. I examined core of the McCracken from the Belco Petroleum Corp. Belco Egnar Unit No. 1 well (number 106, appendix 1, pl. 1). In this well the McCracken consists of interbedded medium- to coarse-grained reddish, bioturbated sandstone, light-gray, silica-cemented quartzite, and red and green shale. In outcrop the McCracken most commonly is a rough-weathering cliff of light-gray to white, fine- to medium-grained, silica-cemented quartzite. Individual sandstone beds are thin to thick bedded; thin sandy shale beds are a minor component. Baars (1966) and Baars and See (1968) said that the McCracken grades laterally into arenaceous dolomite in some places in the outcrops bordering the Needle Mountains. Just south of Coal Bank Pass the top surface of rocks presumed to be McCracken contains scattered pebbles of multicolored, angular quartz. This surface resembles unconformity surfaces in Mesozoic rocks that I have seen elsewhere, wherein the pebbles form a lag deposit on the top of the underlying unit. If the underlying quartzite is really McCracken, then this surface may be an intra-Elbert unconformity. Another possibility is that the entire quartzite here is Ignacio, and the surface represents the Cambrian-Devonian unconformity.

For this report, correlations of the McCracken were also extended outward from the Bluff Unit No. 1 well in southeastern Utah. A marker bed in the overlying upper member of the Elbert aided in locating the McCracken in the section. One problem encountered, and also mentioned by Parker and Roberts (1963, 1966), is that in the subsurface the upper member of the Elbert contains numerous sand bodies similar in lithology to the McCracken. Quartzites were also seen in various outcrops of the upper member of the Elbert around the Needle Mountains. Many of the AMSTRAT sample logs of wells in the Paradox Basin place the top of the McCracken at the top of these sands. A unit thus picked would vary considerably in thickness from area to area and would be notably thicker than the unit shown as McCracken in this report. For this study an attempt was made to correlate the unit originally defined as McCracken, although some miscorrelations were undoubtedly made.

Studies of the McCracken Sandstone Member at outcrops bordering the Needle Mountains reveal other complexities. As originally defined (Cross, 1901), the Cambrian Ignacio Quartzite included the entire quartzite interval above Precambrian rocks and below dolomite and shale of the Elbert Formation. Based on conformable contact relations with the Elbert Formation, Barnes (1954) strongly argued that the Ignacio (as defined by Cross) is Devonian in age. He also thought that the Bakers Bridge Granite had intruded the Ignacio, thus concluding that the granite is post-Devonian in age. This interpretation of the Devonian age of the Ignacio led Cooper (1955) to infer that the Ignacio of the Needle Mountains correlated with the McCracken of the subsurface of the Paradox Basin. Cooper (1955) showed all Cambrian strata pinching out before reaching the outcrop. An unresolved problem was that Cross, Howe, Irving, and Emmons (1905) had discovered a Cambrian-age fossil in the Ignacio at the outcrop.

Baars and Knight (1957) resolved the paradox by suggesting that both Cambrian and Devonian strata are represented in the basal quartzite sequence at the outcrops. They noted subtle lithologic differences between the two units and suggested that only the McCracken Sandstone Member is present at Bakers Bridge. Their interpretation of both Cambrian and Devonian quartzites being present at the outcrop is supported by the following. (1) Rhodes and Fisher (1957) discovered a fossiliferous bed in the lower part of the Ignacio that yielded numerous fossils of Cambrian or Ordovician(?) age. (2) I collected a sample of McCracken quartzite from the Piedra River area, just east of the study area, that contains fragments of Devonian fish bones (C.A. Sandberg, oral commun., 1988). Devonian fish remains have also been collected from the Aneth Formation, which underlies the McCracken in the subsurface (Knight and Cooper, 1955). There is thus evidence from outcrops in the Needle Mountains area that both Cambrian and Devonian fossils are present in quartzite that is present above Proterozoic rocks and below the upper member of the Elbert Formation. Barnes' (1954) suggestion that the Bakers Bridge Granite is post-Devonian has been discounted because the granite has now been isotopically dated at about 1,700 Ma (Tweto, 1987, p. A30), making it Early Proterozoic in age. Based on petrographic studies in progress, there may be evidence that both the Ignacio and McCracken are present at Bakers Bridge (J.A. Campbell, written commun., 1994).

Plate 13 is an isopach map of the McCracken Sandstone Member as used in this report. The McCracken is 0–122 ft thick on the map. It is absent in the southwestern corner of Colorado because of the presence of a basement high (fig. 9). The situation may be similar southeast of Dove Creek, Colo., where no McCracken was identified. This well also is near the axis of the Dolores anticline, which may have affected deposition in this area. The area of thickest McCracken is in an arcuate zone in southeastern Utah. Its distribution there suggests that the Monument upwarp may have had some influence on deposition or preservation of the member.

UPPER MEMBER

The upper member of the Elbert is that unit originally defined by Cross (1904) as comprising the entire Elbert. In

Figure 11. Precambrian and lower Paleozoic rocks exposed at Endlich Mesa on the south side of the Needle Mountains. Eolus Granite is below cliff; cliff is composed of Cambrian Ignacio Quartzite and possibly the McCracken Sandstone Member of the Devonian Elbert Formation. Upper member of the Elbert forms the upper slope. Ouray Limestone is on skyline.

the Needle Mountains the Elbert consists of brown to light-gray, platy dolomite interstratified with maroon to green shale and minor quartzite (fig. 11). Some of the dolomite beds contain salt casts and stromatolites; fish remains are common in some exposures. At two places in the Coal Bank Pass area samples of dolomite that has fracture coatings of malachite and azurite were collected. As described on sample logs, the upper member also contains anhydrite inclusions, pyrite, and a few limestone beds. In the subsurface the interbedded clay is almost always green and is commonly described as waxy. Some intervals of Elbert in the northwestern part of the study area consist of equal amounts of sandstone and dolomite in alternating beds. In core from the Belco Egnar Unit No. 1 well the upper member consists of light-gray dolomite interbedded with green shale. In this well a bed, which seems to be quite widespread and which was used as a marker in some areas, is a highly porous dolomite that has green clay laminations.

Plate 14 is an isopach map of the upper member of the Elbert. The unit ranges in thickness from 50 to 320 ft in the study area. The thickest areas are in the northwest, where the McCracken Sandstone Member grades into the upper member, and in the southwest, near Mexican Hat, Utah. The relative thinness of the McCracken at Mexican Hat possibly indicates that the McCracken grades laterally into the upper member in this area as well. The thinnest areas of the upper member are on the flanks of the Needle Mountains, on the east side of the study area, and over the buried Precambrian high in southwestern Colorado.

The upper member was deposited in shallow subtidal to supratidal environments. The abundance of dolomite and the presence of salt casts and anhydrite inclusions suggest deposition in relatively warm, evaporative environments. The upper member grades westward into a thick sequence of Upper Devonian rocks in central and western Utah where the section is primarily composed of dolomite (Hintze, 1988). Devonian correlatives in the Grand Canyon area also comprise thick dolomite (Beus, 1989). In central Colorado, however, the lower part of the Upper Devonian section (Parting Formation) is composed of sandstone, micaceous, sandy shale, and a few dolomite beds (Campbell, 1972). Campbell (1972, p. 58) noted that the source of sands of the Parting was just to the east of where the Parting was deposited and that the sands were reworked by a transgressing sea. This

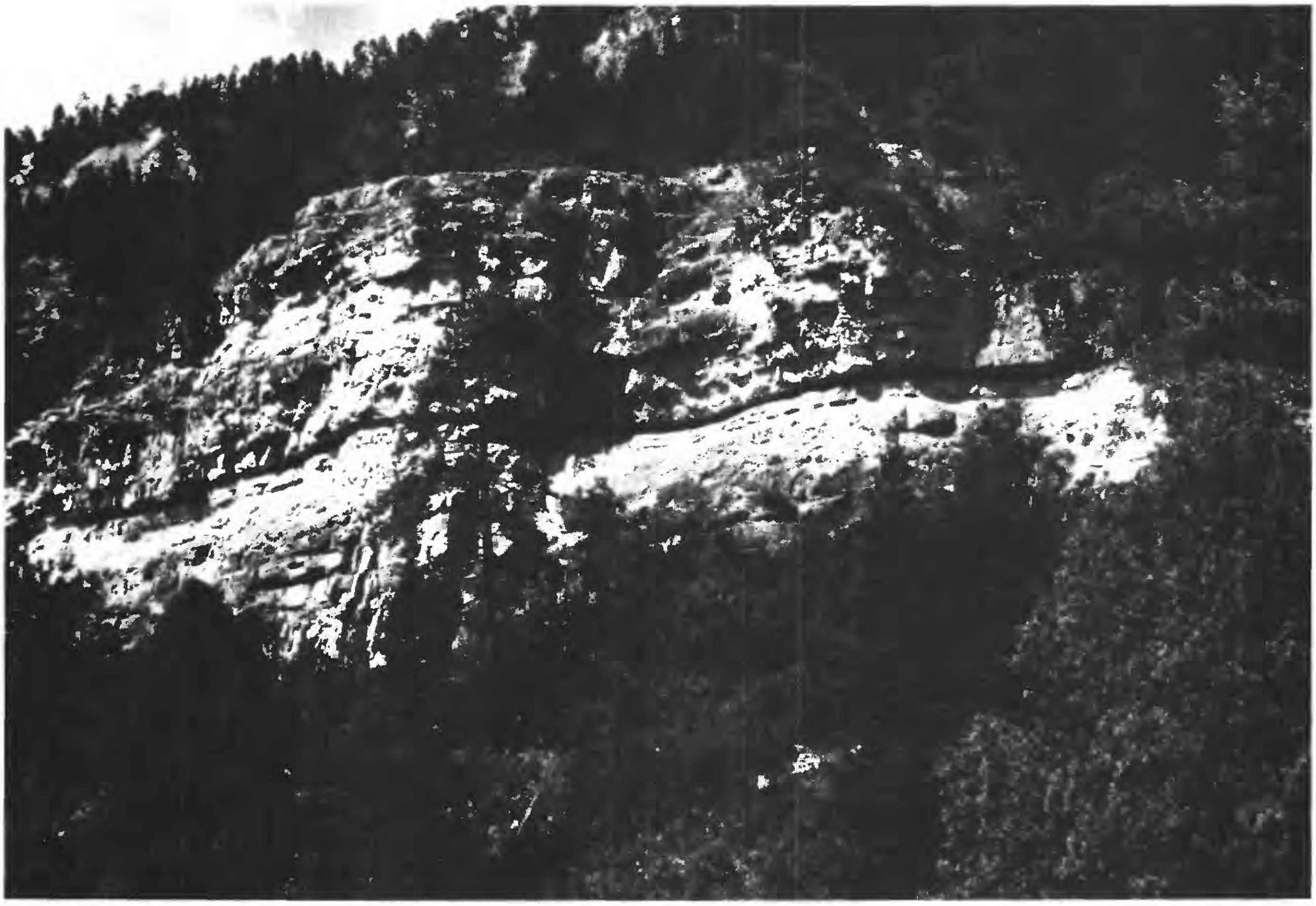


Figure 12. Mississippian Leadville Limestone underlain by Upper Devonian Ouray Limestone at Rockwood Quarry. Leadville Limestone is approximately 115 ft thick. Prominent notch in lower part of cliff approximately marks the contact.

local source area probably represents the continued influence of the Transcontinental arch. The area discussed herein was midway between these highlands in central Colorado and the deep-water miogeocline in western Utah, and the lithology of the Elbert Formation in the Paradox Basin reflects this transitional position on a shallow shelf.

OURAY LIMESTONE

The Ouray Limestone conformably overlies the Elbert Formation. The Ouray was named by Spencer (1900) for Upper Devonian rocks in the area near Ouray, Colo. As originally defined, the Ouray included rocks now assigned to the Elbert Formation, Ouray Limestone, and Leadville Limestone. Later, Girty (1900, 1903) discovered that Mississippian limestones had been included in the unit. Cross and Howe (1907) mapped the lower, shaly part of the unit as Elbert Formation and retained the name Ouray Limestone for the Devonian and Mississippian carbonate rocks above the Elbert. Subsequently Kirk (1931) restricted the Ouray to limestones of Late Devonian age and assigned the Mississippian carbonate rocks to the overlying Leadville Limestone.

At outcrops in the Needle Mountains the Ouray consists of dark-brown, dense, fossiliferous limestone (fig. 12). Parker and Roberts (1966, p. 2418) noted that the Ouray is oolitic in some places, and Baars and See (1968, p. 343) noted a zone of stromatolites at Rockwood Quarry, north of Durango, Colo. Also present at Rockwood Quarry is a green, waxy shale that was considered by Armstrong and Mamet (1977) as the contact with the overlying Leadville Limestone. This shale is also present in the subsurface (figs. 6–9) and was used in this study as the basis for the pick for the top of the Ouray. J.A. Campbell (written commun., 1994) reported that the Devonian-Mississippian contact is about 3 ft above this shale at a wavy bedded dolomitic sandstone or sandy dolomite that is probably equivalent to the Gilman Sandstone of central Colorado.

The Ouray is described on sample logs as a light- to dark-brown to gray limestone that has green to purple clay partings. Crinoid fragments and oolites were noted in some wells. In some wells tan to gray dolomite also is a constituent of the Ouray. Anhydrite inclusions and pyrite were noted in a few wells.

In the Egnar Unit No. 1 core the shale bed at the contact with the Leadville is mainly a fine-grained, medium-gray limestone that has dark-gray clay laminations and pyrite. One interval of the Ouray in this core is composed of nodular carbonate that has abundant green clay layers. This zone is very fossiliferous, containing brachiopods. Most of the Ouray in the core is dense, gray, laminated limestone and dolomite that has a greenish cast from abundant clay partings.

Plate 15 is an isopach map of the Ouray Limestone in the study area. As mapped here, the Ouray ranges from 0 to about 200 ft in thickness. Its thickness is relatively constant in much of the area, commonly between 75 and 125 ft. An interesting area is Wray Mesa, south of Paradox Valley in the northeastern part of the basin (fig. 1). Here the Ouray is missing in at least two wells, possibly due to erosion from the top of an active fault block (Baars, 1966). The area shown on the map between Slick Rock and Gateway, Colo., as having a zero thickness of Ouray is larger than it actually should be. This is due to the effect of widely spaced control points and computer contouring. More closely spaced wells would probably limit the area to a smaller region centering on the wells at Wray Mesa. Erosion probably occurred at the top of the fault block along the Paradox anticline, not in adjacent synclines.

The nature of the contact between the Ouray and enclosing formations has been interpreted differently by different workers. As noted earlier, Kirk (1931) restricted the Ouray to Upper Devonian carbonate rocks in the Needle Mountains area and considered its contacts to be gradational with both the underlying Elbert Formation and the overlying Leadville Limestone. In most areas the distinction of the Ouray from other formations was based on differences in fauna. A Devonian vertebrate fauna characterizes the Elbert, whereas the Ouray contains a Devonian invertebrate fauna. A Mississippian invertebrate fauna distinguishes the Ouray from the Leadville.

This classification of the Ouray prevailed until Baars and Knight (1957) and Knight and Baars (1957) concluded that the Ouray fauna is actually partly Mississippian. They did not find any evidence of an unconformity with the overlying Leadville Limestone in the Needle Mountains and thus considered the Ouray to be both Devonian and Mississippian. Other reports (Baars, 1966; Baars and See, 1968; Parker and Roberts, 1966) also expressed the view that the Ouray is both Devonian and Mississippian. All these reports described the contact of the Ouray with the underlying Elbert as gradational.

More recently Armstrong and Mamet (1977), Armstrong and Holcomb (1989), and Sandberg and others (1989) have shown an unconformity between the Ouray and Leadville. Armstrong and Mamet (1977, p. 113) stated that the boundary between the Ouray and Leadville could not be dated in detail paleontologically. They listed several criteria for distinguishing the two units. (1) The color of the carbonate changes from brownish gray in the Ouray to light gray in the Leadville. (2) Argillaceous material decreases markedly in the Leadville. (3) The Leadville contains intraformational conglomerates not present in the Ouray. (4) The Leadville contains well-developed stromatolites, laminations, and thin-bedded maroon shale. (5) There is evidence of vadose weathering at the top of the shale bed commonly separating the Ouray from the Leadville. This weathering horizon was interpreted to be evidence of an unconformity. Sandberg and others (1989, p. 187) showed an unconformity at the top of the Ouray, based on conodont zonation and an interpreted eustatic sea-level fall. The eustatic fall initiated a Late Devonian mass extinction event and signaled the end of the Devonian Period (Sandberg and others, 1989, p. 211).

The Ouray was deposited on a wide shallow-marine shelf, in conditions similar to those of the underlying Elbert Formation. The relative abundance of green shale may indicate that the highland area in central Colorado was still a source of some clastic material, but the absence of significant amounts of interbedded sandstone in the Ouray implies that the area had subdued topography. The Ouray is considered a correlative of the Dyer Formation of central Colorado (Baars and Campbell, 1968; Baars, 1972; Campbell, 1972), which is a fossiliferous limestone and dolomite unit. The environments of deposition of the Dyer ranged from shallow, warm, slightly agitated marine to intertidal mudflat (Campbell, 1972, p. 58). To the west and southwest, the Ouray correlates with parts of the Pinyon Peak and Fitchville Formations (Beus, 1989; Sandberg and others, 1989).

MISSISSIPPIAN ROCKS

There is only one Mississippian unit in the Paradox Basin; it is known as the Leadville Limestone in the east and as the Redwall Limestone in the west. An overview of the Mississippian System is given in Craig (1972), Craig and Connor (1979), and Poole and Sandberg (1991). A standard reference for the Redwall Limestone is by McKee and Gutschick (1969). Huffman and Condon (1993) considered the lower part of the overlying Molas Formation as Late Mississippian in age in a study of the San Juan Basin. This interpretation was based on previous studies by Merrill and Winar (1958, 1961), who thought that the Mississippian-Pennsylvanian boundary lies within the lower part of the Molas. The lower part of the Molas also is lithologically similar to, and can be correlated in the subsurface with, the Upper Mississippian Log Springs Formation of the southeastern San Juan Basin in northern New Mexico (Huffman and Condon, 1993; Condon and Huffman, 1994). The connection between the Molas Formation of the Paradox Basin and the Log Springs Formation is more tenuous, however, and the Molas is treated as a Pennsylvanian unit in the present report.

LEADVILLE LIMESTONE AND REDWALL LIMESTONE

The Lower and Upper Mississippian Leadville Limestone and correlative Redwall Limestone unconformably overlie Devonian rocks in the study area and are unconformably overlain by Pennsylvanian rocks. The Leadville was named by Eldridge (*in* Emmons and others, 1894) for the chief ore-bearing unit in the Leadville, Colo., mining district. The Redwall was named by Gilbert (1875) for the sheer, reddish cliffs in the Grand Canyon. As with the Cambrian Tintic, Tapeats, and Ignacio formations, there is no clear dividing line between areas where the Leadville and Redwall names are used. Parker and Roberts (1963, 1966) demonstrated that the units are continuous in the subsurface from outcrops in southwestern Colorado to outcrops in Arizona. Foster and others (1968) suggested that both surface and subsurface outcrops in southwestern Colorado use the name Redwall.

In the Needle Mountains area the Leadville consists of massive, gray, fossiliferous limestone and brown dolomite (fig. 12). It and the Redwall Limestone were deposited in a series of upward-shoaling cycles that include a full suite of environments ranging from shallow-marine tidal shelf through lagoonal and supratidal (Kent and Rawson, 1980, p. 106). Exposed erosion surfaces, caused by emergence and erosion of the carbonate rocks, display vadose weathering features (Armstrong and Holcomb, 1989, p. D6). The great variety of depositional environments in the Leadville is reflected in associated diverse faunal assemblages. Armstrong and others (1980, p. 87) cautioned that abrupt facies changes and the numerous erosion surfaces make lithostratigraphic correlations between widely separated locations unreliable.

In many places in the subsurface of the eastern Paradox Basin the lower part of the Leadville is dolomite. This led Baars and Knight (1957) to divide the Leadville into informal upper and lower members, based on the presence of dolomite. Later, Parker and Roberts (1966, p. 2429) pointed out that patterns of dolomitization in the Leadville or Redwall are complex and cannot be used for regional correlations. Baars (1966) and Baars and See (1968) attributed lithologic variations in the Leadville to the influence of paleostructures formed by faulting.

On sample logs the Leadville and Redwall are commonly described as gray to cream limestone and light-brown dolomite, both of which contain abundant crinoid fragments, oolites, and algal laminations. Chert is locally abundant in the upper part of the lower half of the units. In the Belco Egnar No. 1 well (number 106, appendix 1, pl. 1) the Leadville is dense, dark-gray limestone that contains algal laminations and oolites. Light-brown dolomite is also a constituent of the lower part of the Leadville in this well. In one interval the dolomite has been deformed by soft-sediment loading by the overlying darker limestone.

Plate 16 is an isopach map of the Leadville and Redwall Limestones in the Paradox Basin. The thickness of the unit ranges from more than 1,000 ft on the northwestern side to zero on Wray Mesa. This area of zero thickness on Wray Mesa is also an area where the Ouray Limestone is absent. Baars (1966) attributed the absence of both the Ouray and Leadville here to erosion on top of a fault block. The anomalously thin area west of Moab, Utah, is caused by a well in which the unit is faulted. As with the Ouray Limestone, the widely spaced control points and the effect of computer contouring exaggerates the thin places in the Wray Mesa and Moab areas. Otherwise, the Leadville and Redwall thicken from east to west fairly uniformly across the study area.

The Antler orogeny initiated a style of sedimentation in western Utah and eastern Nevada that differed markedly from that during the Cambrian to Devonian (Poole and Sandberg, 1991). Rising highlands shed clastic rocks to the east, partly filling in the marine basin. During deposition of the Leadville and Redwall Limestones, however, the Paradox Basin was far enough east from the highlands that it was not the site of clastic sedimentation. Thick deposits of Mississippian clastics were deposited in western Utah, whereas shallow shelf carbonates were deposited in the east (Gutschick and others, 1980; Hintze, 1988). The main effect of the Antler orogenic activity in the carbonate platform area of the Paradox Basin was to initiate sea-level rises and falls. McKee and Gutschick (1969) and Kent and Rawson (1980) described transgressive and regressive cycles within the Redwall.

Between Late Mississippian and Early Pennsylvanian time the sea withdrew to the west and exposed the top of the Leadville and Redwall to deep erosion (Gutschick and others, 1980, p. 125). This erosion of the carbonate surface produced karst topography and a thick regolith of carbonate blocks, chert, and red shale. The red shale filtered downward into the upper part of the carbonate, making it difficult, in some wells, to decide precisely where to pick the base of the overlying Molas Formation.

PENNSYLVANIAN ROCKS

Mississippian rocks of the Paradox Basin are everywhere overlain unconformably by Pennsylvanian rocks. In most of the basin the Molas Formation is the basal Pennsylvanian unit; however, in a few places the Molas is missing, and rocks of the Hermosa Group overlie the Mississippian.

The Molas consists of a basal regolith deposit, middle fluvial strata, and upper fluvial and marine limestone beds (Merrill and Winar, 1958, 1961). The lower unit, called the Coalbank Hill Member by Merrill and Winar (1958), is composed of conglomerate and limestone-chert breccia and reddish-brown mudstone and siltstone. In some places in the Needle Mountains the Leadville is absent, and the regolith overlies the Ouray Limestone.

The middle member of the Molas is composed of stratified conglomerate, sandstone, siltstone, and shale that were deposited in a fluvial system. Lithologies of the upper member are similar to those of the middle member but also include limestone beds containing Pennsylvanian marine fossils. This change in lithology documents the changing environments of deposition of the Molas from karst plain at the base to shallow marine at the top.

Merrill and Winar (1958, 1961) discussed the Mississippian-Pennsylvanian boundary in relation to the Leadville Limestone and Molas Formation. They noted that the youngest Leadville in the Needle Mountains area is of Osagean age, an age later verified by the studies of Armstrong and Mamet (1977) and Armstrong and Holcomb (1989). An unknown thickness of younger Mississippian rocks may have once been deposited in that area and then removed by erosion or dissolved in place on the karst plain. The karst plain was apparently stable for quite a long time because a thick regolith developed on top of the Leadville and red silt and shale filtered downward and filled fractures and cavities in the upper part of the Leadville. No fossil data are available for this regolith with which to accurately place the systemic boundary, but the boundary probably lies within the regolith.

A unit in the Nacimiento Mountains on the eastern side of the San Juan Basin may offer some clues as to the age of the basal Molas strata. The Log Springs Formation was defined by Armstrong (1955) and is described as a continental clastic redbed unit composed of conglomerate, arkosic sandstone, and shale. The Log Springs is considered to be of Late Mississippian age (Armstrong and Mamet, 1977, p. 122), and occupies a stratigraphic position similar to that of the Molas Formation. Condon and Huffman (1994) showed that the Molas and Log Springs have similar geophysical log characteristics and can be correlated in the subsurface of the San Juan Basin. Because of stratigraphic position and lithologic similarity, the basal beds of the Molas in the northern San Juan Basin are considered equivalent to the Log Springs and therefore may be Mississippian in age. These beds may well be diachronous, however, and the Molas farther to the west in the Paradox Basin may be entirely Pennsylvanian. Without a dated unit, such as the Log Springs, near by, assigning a Mississippian age to basal Molas strata in the Paradox Basin is unwarranted.

SUMMARY

Relatively little is known about Precambrian paleogeography and precursor events in the Paradox Basin area that led to the Phanerozoic, even though the time involved is much longer and the thickness of rocks is much greater. What has been deduced, mainly from studies of outcropping Precambrian rocks in Colorado, New Mexico, and Arizona, is that by approximately 1,800 Ma collisions had begun to juxtapose the older Archean craton, at what is now the southern border of Wyoming, with offshore magmatic arcs at a convergent plate boundary. The subduction zone at the boundary is postulated to have first dipped southward and then reversed and dipped to the north (Condie, 1982; Anderson, 1989a). Sedimentation in continental back-arc basins also occurred in conjunction with the collision events. Products of this sedimentation underlie much of the Paradox Basin. As a result of the accretion process, much of the Precambrian terrane of the southwestern United States is characterized by northeasterly trending belts of Proterozoic rocks that are younger southward.

Metamorphism also accompanied accretion, altering the volcanic and sedimentary components of the magmatic arcs and back-arc basins to gneiss, schist, amphibolite, and other metamorphic rock types. An early period of intrusive igneous activity occurred at this time, emplacing granodiorites and other felsic igneous rocks. A somewhat uncommon rock unit, the Uncompahgre Formation of southwestern Colorado, was deposited after about 1,695 Ma and before 1,435 Ma. The Uncompahgre, mostly a quartzite but with some argillaceous layers, was deposited on the underlying gneiss complex. The youngest Precambrian rocks in the eastern part of the study area are a group of felsic intrusive rocks that were emplaced at about 1,435–1,400 Ma to as late as 1,350 Ma. There is some evidence suggesting that a younger Proterozoic supracrustal sedimentary sequence was deposited in the western part of the study area. Rocks having lithologies similar to the Grand Canyon Supergroup or to the Uinta Mountain Group have been identified in scattered wells in southeastern Utah and northeastern Arizona. These rocks may have accumulated in a lacustrine setting near the edge of the Proterozoic craton. If equivalent, in part, to the Grand Canyon Supergroup, these rocks are in the 1,250–800-Ma time range.

After a long period of erosion, pre-Mississippian stratigraphic units in the Paradox Basin were deposited under fairly uniform conditions. Pre-Mississippian sedimentation was mostly controlled by the area's position on a shallow cratonic shelf adjacent to the Cordilleran miogeocline. To the west of the current position of the basin many thousands of feet of Cambrian through Devonian strata were deposited in a marine basin (figs. 3, 4). To the east, for most of this time, were relatively low upland areas of the Transcontinental arch that periodically shed clastic material to the shelf. Shelf conditions persisted in the area of the Paradox Basin during deposition of Mississippian rocks, even though tectonic activity was intense west of the Wasatch line. Pre-Pennsylvanian sedimentary rocks in the Paradox Basin form a westward-thickening wedge of clastic and carbonate rocks deposited on the shelf (pl. 17).

From a global perspective, the basin was at low latitudes from Cambrian through Mississippian time (Habicht, 1979; Hintze, 1988, p. 25). Revised world paleogeographic maps by Scotese and McKerrow (1990) indicate that in latest

Precambrian time the craton (Laurentia) was rotated such that the Equator passed almost through the Paradox Basin and was oriented just a little east of north with respect to present-day north. During the Cambrian the craton slowly rotated counterclockwise, such that by the Late Cambrian the area of the Paradox Basin was just south of the Equator. Counterclockwise rotation continued into the Orodovician but slowed or stopped in the Silurian and Devonian. At the end of the Devonian the area of the Paradox Basin was positioned at about lat 15° S. This represents a slight northward shift from the Middle Devonian and may be a result of earliest contact with Gondwana. In the Mississippian, the orientation of the craton with respect to the Equator remained about the same, but the craton drifted even farther northward, placing the area of the Paradox Basin just south of the Equator. The climate of the North American craton was interpreted as being hot to warm for most of the Cambrian through Mississippian (Scotese and McKerrow, 1990, p. 18).

Earliest Cambrian sedimentation must have been on a surface of at least moderate relief because Cambrian strata at various places in the Paradox Basin include quartzite-pebble, quartz-pebble, and arkosic conglomerate at the base. Some of these conglomerates may even have been deposited in the late Precambrian. A basal conglomerate is also characteristic of the Cambrian in areas as widely separated as the Grand Canyon, central Utah, and central Colorado.

The area of the Paradox Basin was quite stable for most of Middle and Late Cambrian time. Upper strata of the Tintic Quartzite contain shaly beds, and the Tintic is overlain gradationally by the Ophir Formation (or Shale), indicating marine transgression from the west. The shoreline trended north-northeasterly during the Cambrian, although the pattern of preserved Cambrian rocks in west-central Colorado suggests that an embayment may have been present in that area. Maximum transgression of the Ophir was accompanied by carbonate deposition of the Maxfield Limestone farther to the west. Sea-level fall may have resulted in erosion of the Maxfield over the central and eastern parts of the Paradox Basin, but it is more likely that the unit was not deposited much farther east than about the Colorado River. A period of regression after the Maxfield was followed by another cycle of transgression during which upper shales of the Ophir and the Lynch Dolomite were deposited.

Another period of erosion separated the Late Cambrian and the Late Devonian in the Paradox Basin. No Ordovician, Silurian, or Lower and Middle Devonian rocks have been identified in the basin; if any were ever deposited, they would have been relatively thin. The stability of the shelf continued through this time, however, because Upper Cambrian and Upper Devonian strata are parallel.

The oldest Upper Devonian unit in the basin, the Aneth Formation, was deposited in a euxinic marine environment. The Aneth is considered by some to extend over a much greater area than that shown in this report, but lithologic logs of basal Upper Devonian strata in other areas of the basin do not support that interpretation. Dark-gray to black shale is a characteristic component of the Aneth in and near the area where it was originally described. In other areas, basal Devonian strata are composed of either sandstone or green shale and dolomite.

The McCracken Sandstone Member is the basal sandstone of the Elbert Formation. The interpretation favored here is that the McCracken represents sands that were reworked and distributed as a result of marine transgression following sea-level fall in post-Aneth time. Some of the Parting Formation, of central Colorado, is equivalent to the McCracken, and the source of sands in the Parting was highlands a short distance to the east and northeast of where the formation was deposited. These sands were probably carried westward by fluvial systems during the hiatus between the Aneth and McCracken and then reworked during the marine transgression. Shallow-shelf conditions prevailed during this time.

Sandstones in the upper member of the Elbert Formation suggest that the highlands to the east continued to shed clastics onto the shelf during deposition of the upper member. The distribution of sandstones as far west as the western part of the Paradox Basin during this time may indicate minor fluctuations of sea level and associated shifting of the shoreline facies. The upper part of the upper member consists mainly of dolomite and shale, indicating a further rise in sea level during this time and only a minor contribution of clastics from the east.

Even less influx of clastics is evident in the overlying Ouray Limestone. The Ouray contains a diverse marine fauna indicating deposition in warm, shallow, normal marine conditions. The Ouray extends southeastward into New Mexico and has equivalents in central Colorado. Its position in the Paradox Basin is thus about midway on the shallow cratonic shelf. Detailed studies have not been done on the Ouray to discover any transgressive-regressive cycles in the unit.

Sandberg and others (1989) described a catastrophic fall in sea level in the Late Devonian that resulted in widespread extinctions and the end of the Devonian Period. This event should mark the contact between the Ouray Limestone and the overlying Mississippian Leadville Limestone and correlative Redwall Limestone; however, there is little physical evidence of this event in the Paradox Basin. A shale bed lies just below the contact of the Ouray and overlying strata in much of the basin, and there is little evidence of erosion or channeling at the top of the Ouray; bedding in the overlying Leadville and Redwall Limestones is essentially parallel to that in the Ouray.

Regardless of the basal contact, the Leadville and Redwall were also deposited in a warm, shallow, normal marine environment. In response to tectonic activity in western Utah and eastern Nevada, Mississippian rocks of the Paradox Basin display several transgressive-regressive cycles of deposition. Fluctuating sea level led to the development of diverse depositional environments and faunal assemblages that are a result of differing energy conditions in the shallow sea. A major sea-level fall during deposition of the Leadville and Redwall led to a widespread intraformational disconformity that is marked by dolomite and chert in much of the area.

A final fall of sea level resulted in the end of Mississippian carbonate deposition and exposure of the carbonates to subaerial erosion. The position of the Paradox Basin near the Equator at this time suggests that humid conditions prevailed, leading to development of the Molas Formation, a clay-rich, red regolith at the top of the Leadville and Redwall. Solution of the carbonate surface formed fissures, caves, and karst topography that was mantled by red clay. The transition from Mississippian to Pennsylvanian time probably occurred sometime during deposition of this regolith, but no faunal or isotopic data exist with which to precisely place the boundary. A similar redbed unit in northwestern New Mexico (Log Springs Formation) is considered to be Mississippian, but the connection between the Molas of the Paradox Basin and the Log Springs is tenuous. Final withdrawal of the Mississippian sea exposed areas east of the Paradox Basin before the top of the Mississippian within the Paradox Basin was exposed. The Molas of all or most of the Paradox Basin could therefore be entirely of Pennsylvanian age. At the close of Mississippian time, the region of the Paradox Basin lay basking in the warm equatorial sun, and there was little indication of the dramatic tectonic and environmental changes that were to modify the area during the coming Pennsylvanian and Permian Periods.

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APPENDIXES

APPENDIX 1—DRILLHOLES USED AS CONTROL POINTS FOR MAPS AND CROSS SECTIONS

This listing is sorted by township, range, and section within States. The last two digits in the location column denote the position of the well within the section; each section is divided into 16 parts—number 01 is in the NE¼NE¼ and number 16 is in the SE¼SE¼. The divisions are numbered horizontally. Comments: 1, Hole reached Precambrian but was not logged by AMSTRAT; 2, AMSTRAT log was not available to the author; 3, No Precambrian lithology was logged by AMSTRAT; 4, Description is from AMSTRAT or other source; 5, Well cuttings were examined by the author. Leaders (--) indicate that well did not reach Precambrian.

No.	Company	Well name	Location	County	Description of Precambrian lithology from AMSTRAT log or other sources	Author's description of cuttings	Comment
			ARIZONA				
1	Buttes Gas and Oil Co.	Navajo 1576 No. 1–31	T. 35 N., R. 27 E., sec. 31, 01	Apache	Granite	--	4
2	Buttes Gas and Oil Co.	Navajo 8850 No. 1	T. 35 N., R. 28 E., sec. 5, 05	Apache	Metamorphic	--	4
3	Buttes Gas and Oil Co.	Navajo No. 1–25	T. 35 N., R. 28 E., sec. 25, 16	Apache	Metamorphic	--	4
4	Curtis J. Little and E.R. Richardson	Tohotso Navajo No. 1	T. 35 N., R. 29 E., sec. 25, 13	Apache	Granite wash	--	4
5	Anadarko Production Co.	Navajo No. 1–135	T. 35 N., R. 30 E., sec. 3, 04	Apache	Granite	--	4
6	Humble Oil and Refining Co.	Navajo 138 No. 1	T. 35 N., R. 30 E., sec. 6, 08	Apache	Unknown	--	3
7	Humble Oil and Refining Co.	Navajo 138 No. 2	T. 35 N., R. 30 E., sec. 6, 16	Apache	--	--	--
8	Humble Oil and Refining Co.	Navajo 140 No. 1	T. 35 N., R. 30 E., sec. 8, 08	Apache	Granite	--	4
9	Kerr McGee Corp.	Navajo H No. 1	T. 35 N., R. 30 E., sec. 14, 01	Apache	--	--	--
10	Humble Oil and Refining Co.	Navajo 146 No. 1	T. 35 N., R. 30 E., sec. 15, 14	Apache	Unknown	--	1
11	Humble Oil and Refining Co.	Navajo 151 No. 1	T. 35 N., R. 30 E., sec. 35, 08	Apache	Granite	--	4
12	Cactus Drilling Corp.	Navajo 85–15 No. 1	T. 36 N., R. 22 E., sec. 14, 04	Apache	Granite	Quartz diorite	5
13	Riddle and Gottlieb	Navajo 8841 No. 1	T. 36 N., R. 27 E., sec. 30, 05	Apache	--	--	--
14	Vaughey, Vaughey, and Blackburn	Navajo 8805 No. 6–1	T. 36 N., R. 28 E., sec. 6, 04	Apache	--	--	--
15	Union Oil Co. of California	Navajo 3741 Lukachukai No. 1–P–4	T. 36 N., R. 29 E., sec. 4, 16	Apache	--	--	--
16	Union Oil Co. of California	Navajo N 11 Lukachukai No. 1	T. 36 N., R. 29 E., sec. 11, 14	Apache	Diorite	Granite	5
17	Humble Oil and Refining Co.	Navajo 87 No. 1	T. 36 N., R. 29 E., sec. 23, 08	Apache	Metamorphic	Quartzite	5
18	Humble Oil and Refining Co.	Navajo 88 No. 2	T. 36 N., R. 29 E., sec. 25, 08	Apache	Granite	--	4
19	Kerr McGee Corp.	Navajo E No. 1	T. 36 N., R. 30 E., sec. 20, 16	Apache	Unknown	--	1
20	Kerr McGee Corp.	Navajo No. 8	T. 36 N., R. 30 E., sec. 29, 16	Apache	Unknown	--	1
21	Kerr McGee Corp.	Navajo No. 10	T. 36 N., R. 30 E., sec. 30, 08	Apache	Unknown	--	1
22	Kerr McGee Corp.	Navajo No. 5	T. 36 N., R. 30 E., sec. 31, 16	Apache	Unknown	--	1
23	Kerr McGee Corp.	Navajo No. 1	T. 36 N., R. 30 E., sec. 32, 14	Apache	Metamorphic	--	4
24	Champlin Petroleum Co.	Navajo No.1	T. 37 N., R. 25 E., sec. 04, 10	Apache	Unknown	--	1
25	Buttes Gas and Oil Co.	Navajo No. 1–24	T. 37 N., R. 28 E., sec. 24, 09	Apache	--	--	--
26	Gulf Oil Corp.	Navajo BS No. 1	T. 37 N., R. 29 E., sec. 12, 02	Apache	Granite	--	4
27	Odessa Natural Gas Co.	Aircodessa Cove No. 1	T. 37 N., R. 29 E., sec. 33, 16	Apache	Granite?	--	4
28	Vaughey, Vaughey, and Blackburn	Navajo No. 35–1	T. 37 N., R. 29 E., sec. 35, 04	Apache	Granite	--	4
29	Gulf Oil Corp.	Navajo CS No. 1	T. 37 N., R. 30 E., sec. 34, 01	Apache	Granite	--	4
30	Superior Oil Co.	Navajo W No. 21–29	T. 38 N., R. 21 E., sec. 29, 03	Navajo	Granite	Metasedimentary	5
31	Excel Energy Corp.	Navajo No. 29–1	T. 38 N., R. 24 E., sec. 29, 07	Apache	Unknown	Quartzite	5
32	Pan American Petroleum Corp.	Navajo Tribal T No. 1	T. 38 N., R. 27 E., sec. 20, 16	Apache	Granite	--	4

33	Skelly Oil Co.	Navajo Q No. 1	T. 38 N., R. 30 E., sec. 18, 04	Apache	--	--	--
34	Texaco Inc.	Navajo AM No. 1	T. 39 N., R. 21 E., sec. 36, 03	Navajo	Andesite or trachyte	Metasedimentary	5
35	Superior Oil Co.	Navajo V No. 22–12	T. 39 N., R. 23 E., sec. 12, 06	Apache	Metamorphic	Metasediments	5
36	Superior Oil Co.	Navajo V No. 33–12	T. 39 N., R. 23 E., sec. 12, 10	Apache	Metamorphic	--	4
37	Horizon Oil and Gas Co. of Texas	Navajo Mobil No. 1–24	T. 39 N., R. 23 E., sec. 24, 12	Apache	Unknown	--	1
38	J.C. Mann Drilling Co.	Navajo Mobil No. 1	T. 39 N., R. 25 E., sec. 16, 04	Apache	Quartzite	Metasedimentary	5
39	Mobil Oil Co.	Navajo 155 No. 1	T. 39 N., R. 25 E., sec. 28, 06	Apache	Metamorphic	--	4
40	Cactus Drilling Corp.	Navajo Rock Point No. 1	T. 39 N., R. 26 E., sec. 19, 12	Apache	--	--	--
41	Pan American Petroleum Corp.	Tohlacon Navajo No. 1	T. 40 N., R. 25 E., sec. 11, 09	Apache	Metamorphic	Metasedimentary	5
42	Pan American Petroleum Corp.	Navajo F No. 1	T. 40 N., R. 28 E., sec. 6, 12	Apache	Quartzite	--	4
43	Curtis J. Little	West Dry Mesa Navajo No. 1	T. 40 N., R. 28 E., sec. 9, 04	Apache	Quartzite	--	4
44	Texas Pacific Coal and Oil Co.	Navajo 138 No. 1	T. 40 N., R. 28 E., sec. 11, 01	Apache	Quartzite	--	4
45	Texas Pacific Coal and Oil Co.	Navajo 138 No. 4	T. 40 N., R. 28 E., sec. 11, 03	Apache	Quartzite	--	4
46	Texas Pacific Coal and Oil Co.	Navajo 138 No. 2	T. 40 N., R. 28 E., sec. 12, 05	Apache	Quartzite	--	4
47	Fee Oil and Gas Ltd.	Navajo No. 1	T. 40 N., R. 28 E., sec. 16, 06	Apache	Unknown	--	1
48	Western States Petroleum Co.	Navajo No. 2	T. 40 N., R. 28 E., sec. 17, 02	Apache	Quartzite	--	4
49	E.B. LaRue, Jr.	Navajo No. 1	T. 40 N., R. 28 E., sec. 18, 04	Apache	Quartzite	--	4
50	American Fuels Corp.	Navajo C No. 1	T. 40 N., R. 29 E., sec. 6, 13	Apache	Quartzite	--	4
51	Atlantic Refining Co.	Navajo No. 7–1	T. 40 N., R. 29 E., sec. 7, 16	Apache	Quartzite	--	4
52	Pan American Petroleum Corp.	Moko Navajo No. 1	T. 40 N., R. 29 E., sec. 15, 11	Apache	Quartzite	--	4
53	American Fuels Corp.	Navajo AC No. 1	T. 40 N., R. 29 E., sec. 17, 01	Apache	Quartzite	--	4
54	Cities Service Oil and Gas Corp.	Monsanto Navajo B No. 1	T. 40 N., R. 29 E., sec. 27, 07	Apache	Quartzite	--	4
55	Depco Inc.	Navajo No. 1–2	T. 40 N., R. 30 E., sec. 2, 10	Apache	Metamorphic?	--	4
56	British American Oil Producing Co.	Navajo C No. 1	T. 40 N., R. 30 E., sec. 5, 13	Apache	Metamorphic	--	4
57	Occidental Petroleum Corp.	Monument Navajo No. 1	T. 41 N., R. 22 E., sec. 12, 12	Apache	--	--	--
58	Gulf Oil Corp.	Garnet Ridge Navajo No. 1	T. 41 N., R. 24 E., sec. 16, 01	Apache	--	--	--
59	Texaco Inc.	Navajo AG No. 1	T. 41 N., R. 25 E., sec. 16, 10	Apache	Metamorphic	Metasedimentary	5
60	Great Western Drilling Co.	El Paso Navajo No. 1	T. 41 N., R. 25 E., sec. 20, 01	Apache	Metamorphic	Metasedimentary	5
61	Texaco Inc.	Navajo AG No. 2	T. 41 N., R. 25 E., sec. 21, 02	Apache	Metamorphic	Metasedimentary	5
62	Tenneco Oil Co.	Navajo 4332 No. 1	T. 41 N., R. 26 E., sec. 33, 13	Apache	--	--	--
63	Shell Oil Co.	Navajo No. 2	T. 41 N., R. 28 E., sec. 3, 06	Apache	--	--	--
64	Superior Oil Co.	Navajo H No. 14–16	T. 41 N., R. 30 E., sec. 16, 13	Apache	Quartzite	--	4
65	Pan American Petroleum Corp.	Navajo O No. 1	T. 41 N., R. 30 E., sec. 23, 14	Apache	Quartzite	--	4
66	Texaco Inc.	Navajo Z No. 1	T. 41 N., R. 30 E., sec. 36, 12	Apache	Olivine gabbro	--	4
			COLORADO				
67	Pure Oil Co.	Gateway Unit No. 1	T. 15 S., R. 104 W., sec. 15, 13	Mesa	Quartz	--	4
68	Continental Oil Co.	Ute Mountain No. 1	T. 32 N., R. 19 W., sec. 7, 04	Montezuma	Granite	--	4
69	Wintershall Corp.	Sidewinder No. 15–11	T. 32 N., R. 20 W., sec. 15, 04	Montezuma	Unknown	Quartzite	5
70	Pan American Petroleum Corp.	Ute Mountain Tribal No. 1	T. 32 N., R. 20 W., sec. 24, 13	Montezuma	Granite	--	4
71	Stanolind Oil and Gas Co.	Ute Indians B No. 6	T. 33 N., R. 7 W., sec. 17, 06	La Plata	Amphibolite and gneiss	--	4
72	Amoco Production Co.	Jessie Hahn No. 1	T. 33 N., R. 8 W., sec. 15, 14	La Plata	Unknown	Granite	5
73	Skelly Oil Co.	Lloyd Benton No. 1	T. 33 N., R. 13 W., sec. 15, 07	La Plata	--	--	
74	California Oil Co.	Ute Tribal No. 1	T. 33 N., R. 19 W., sec. 22, 04	Montezuma	Granite	--	4

No.	Company	Well name	Location	County	Description of Precambrian lithology from AMSTRAT log or other sources	Author's description of cuttings	Comment
			COLORADO—Continued				
75	General Petroleum Corp.	Kikel No. 55–17	T. 34 N., R. 11 W., sec. 17, 10	La Plata	--	--	--
76	El Paso Natural Gas Co.	Butler Pool Unit 1 No. 44–28	T. 34 N., R. 12 W., sec. 28, 06	La Plata	--	--	--
77	Houston Oil and Minerals Corp.	Ute Mountain No. 44-34	T. 34 N., R. 14 W., sec. 34, 16	Montezuma	--	--	--
78	Reynolds Mining Corp.	Point Lookout No. 1	T. 36 N., R. 14 W., sec. 18, 09	Montezuma	--	--	--
79	Texaco Inc.	M.L. Smithson No. 1	T. 36 N., R. 16 W., sec. 19, 10	Montezuma	Unknown	Granite	5
80	Shell Oil Co.	Federal 23–36–17 No. 1	T. 36 N., R. 17 W., sec. 23, 16	Montezuma	--	--	--
81	Shell Oil Co.	Federal 9-36–18 No. 1	T. 36 N., R. 18 W., sec. 9, 08	Montezuma	--	--	--
82	Read and Stevens Inc.	Shenandoah Veach No. 1	T. 37 N., R. 15 W., sec. 2, 13	Montezuma	--	--	--
83	Shell Oil Co.	State No. 1	T. 37 N., R. 16 W., sec. 4, 16	Montezuma	--	--	--
84	Gulf Oil Corp.	Fulks No. 1	T. 37 N., R. 17 W., sec. 27, 04	Montezuma	--	--	--
85	Shell Oil Co.	Federal 36–37–18 No. 1	T. 37 N., R. 18 W., sec. 36, 09	Montezuma	--	--	--
86	Hathaway Co.	USC No. 1	T. 37 N., R. 20 W., sec. 11, 15	Montezuma	--	--	--
87	Gulf Energy and Minerals Co.	Dolores River Unit No. 1	T. 38 N., R. 13 W., sec. 2, 15	Montezuma	--	--	--
88	Great Western Drilling Co.	Tully State No. 1	T. 38 N., R. 14 W., sec. 18, 14	Montezuma	--	--	--
89	Mobil Oil Co.	Cow Canyon Unit No. 1	T. 38 N., R. 19 W., sec. 13, 04	Montezuma	--	--	--
90	Gulf Oil Corp.	South Stoner Creek Federal No. 2	T. 39 N., R. 12 W., sec. 18, 01	Dolores	--	--	--
91	California Oil Co.	Stoner Creek Unit No. 1	T. 39 N., R. 13 W., sec. 18, 07	Dolores	--	--	--
92	California Oil Co.	House Creek Unit No. 1	T. 39 N., R. 14 W., sec. 19, 12	Montezuma	--	--	--
93	Ray Smith Drilling Co.	Chester Brown No. 1	T. 40 N., R. 13 W., sec. 13, 10	Dolores	Latite porphyry	--	4
94	Santa Fe Energy Co.	Narraguinnep Federal No. 1–35	T. 40 N., R. 16 W., sec. 35, 12	Dolores	--	--	--
95	Sinclair Oil and Gas Co.	Glade Canyon Unit No. 1	T. 40 N., R. 17 W., sec. 13, 01	Dolores	--	--	--
96	Shell Oil Co.	Doe Canyon Unit No. 1	T. 40 N., R. 18 W., sec. 15, 01	Dolores	--	--	--
97	Continental Oil Co.	Big Canyon Unit No. 1	T. 41 N., R. 18 W., sec. 17, 16	Dolores	--	--	--
98	Read and Stevens Inc.	Shenandoah Pinto No. 1–X	T. 42 N., R. 18 W., sec. 34, 06	Dolores	--	--	--
99	Kerr McGee Oil Industries	Placerville No. 1	T. 43 N., R. 11 W., sec. 11, 01	San Miguel	Hornblende-biotite gneiss	--	4
100	Exxon Co. USA	Thomas Mountain Federal No. 1	T. 43 N., R. 15 W., sec. 12, 04	San Miguel	--	--	--
101	Read and Stevens Inc.	Slick Rock Federal No. 1	T. 43 N., R. 17 W., sec. 08, 09	San Miguel	--	--	--
102	Reynolds Mining Corp.	Egnar No. 1	T. 43 N., R. 19 W., sec. 14, 04	San Miguel	--	--	--
103	Fred H. Turner	Buss No. 1	T. 44 N., R. 13 W., sec. 26, 14	San Miguel	Biotite gneiss, sed. source	--	4
104	Amoco Production Co.	Naturita Creek Unit No. 1	T. 44 N., R. 13 W., sec. 34, 03	San Miguel	Unknown	Quartz diorite	5
105	Union Oil Co. of California	Mcintyre Canyon Unit No. 3	T. 44 N., R. 19 W., sec. 16, 05	San Miguel	--	--	--
106	Belco Petroleum Corp.	Egnar Unit No. 1	T. 44 N., R. 19 W., sec. 30, 08	San Miguel	--	--	--
107	L.W. Whitlock	Swanson No. 1–A	T. 45 N., R. 8 W., sec. 15, 01	Ouray	--	--	--
108	Davis Oil Co.	McClure No. 1	T. 45 N., R. 9 W., sec. 30, 06	Ouray	--	--	--
109	Penrose and Tatum	Orme No. 1	T. 45 N., R. 10 W., sec. 18, 07	Montrose	Microcline granite, monzonite, syenite	--	4
110	Penrose and Tatum	Marie Scott No. 5	T. 45 N., R. 12 W., sec. 2, 06	Montrose	--	--	--
111	Shell Oil Co.	Shell Federal No. 21–19	T. 45 N., R. 13 W., sec. 19, 03	San Miguel	--	--	--
112	Shell Oil Co.	Gypsum Valley West No. 1	T. 45 N., R. 19 W., sec. 26, 09	San Miguel	--	--	--
113	Odessa Natural Corp.	Buckhorn Fee No. 1	T. 46 N., R. 7 W., sec. 17, 06	Ouray	Unknown	--	1
114	Pure Oil Co.	Red Canyon Nose No. 1	T. 46 N., R. 12 W., sec. 6, 04	Montrose	Unknown	--	1

115	Pure Oil Co.	East Horsefly USA No. 2	T. 46 N., R. 12 W., sec. 21, 12	Montrose	Unknown	--	1
116	Pure Oil Co.	East Horsefly Prospect No. 1	T. 46 N., R. 12 W., sec. 26, 07	Montrose	Unknown	--	1
117	Pure Oil Co.	Horsefly Unit No. 1	T. 46 N., R. 13 W., sec. 14, 11	Montrose	--	--	--
118	Odessa Natural Corp.	Buckhorn 8477 Fee No. 1	T. 47 N., R. 7 W., sec. 8, 05	Montrose	--	--	--
119	Odessa Natural Corp.	Billy Creek No. 2	T. 47 N., R. 8 W., sec. 26, 06	Ouray	Unknown	Quartzite?	5
120	Miami Oil Producers Inc.	Kirby Government No. 1	T. 47 N., R. 15 W., sec. 10, 06	Montrose	--	--	--
121	Bureau of Reclamation	Injection Test Well No. 1	T. 47 N., R. 18 W., sec. 30, 16	Montrose	Diorite, gabbro, schist	--	4
122	Shell Oil Co.	Wray Mesa Unit No. 1	T. 47 N., R. 19 W., sec. 21, 15	Montrose	Quartz monzonite, granodiorite	--	4
123	Shell Oil Co.	Wray Mesa Unit No. 2	T. 47 N., R. 19 W., sec. 32, 03	Montrose	Quartzite	--	4
124	Tipperary Oil and Gas Co.	Holman No. 1	T. 48 N., R. 8 W., sec. 35, 05	Montrose	Unknown	--	1
125	St Helens Petroleum Corp.	Sandberg Unit No. 1	T. 49 N., R. 8 W., sec. 15, 08	Montrose	Biotite gneiss	--	4
126	Texaco Inc.	J.L. Stivers No. 1	T. 49 N., R. 10 W., sec. 9, 08	Montrose	Gneiss, sed. source	--	4
127	Mobil Oil Corp.	Moon Mesa Unit No. 1	T. 49 N., R. 16 W., sec. 31, 13	Montrose	--	--	
128	North American Royalties	Altex Sinbad No. 1	T. 49 N., R. 19 W., sec. 16, 13	Mesa	Unknown	--	1
129	L.A. Messmer	Allyn No. 1	T. 50 N., R. 7 W., sec. 21, 15	Montrose	Unknown	--	1
130	R.E. Weir	Fee No. 1	T. 50 N., R. 10 W., sec. 27	Montrose	Biotite gneiss, sed. source	--	4
			NEW MEXICO				
131	Tenneco Oil Co.	PAH No. 1	T. 25 N., R. 11 W., sec. 3	San Juan	Metamorphic	--	4
132	Amoco Production Co.	Navajo Tribal AH No. 1	T. 25 N., R. 17 W., sec. 10, 06	San Juan	Unknown	Quartzite	5
133	Champlin Petroleum Co.	Navajo Humble No. 1	T. 25 N., R. 19 W., sec. 16, 02	San Juan	Granite	--	4
134	Brooks Hall Oil Corp.	Navajo Tribe AO No. 2	T. 25 N., R. 19 W., sec. 22, 11	San Juan	Unknown	--	1
135	Texaco Inc.	Navajo Tribe AO No. 1	T. 25 N., R. 19 W., sec. 33, 01	San Juan	Schist	--	4
136	Skelly Oil Co.	Navajo O No. 1	T. 26 N., R. 14 W., sec. 34, 14	San Juan	Quartzite	--	4
137	Pure Oil Co.	Navajo No. 27–1	T. 26 N., R. 15 W., sec. 32, 08	San Juan	Granite	--	4
138	Pan American Petroleum Corp.	Navajo Tribal U No. 3	T. 26 N., R. 18 W., sec. 16, 13	San Juan	Unknown	--	1
139	Texaco Inc.	Navajo Tribe AL No. 1	T. 26 N., R. 18 W., sec. 28, 08	San Juan	Granite	--	4
140	Ashland Oil Inc.	Navajo No. 5–2	T. 26 N., R. 19 W., sec. 5, 12	San Juan	Unknown	--	2
141	Amerada Petroleum Corp.	Navajo No. 381-1	T. 26 N., R. 19 W., sec. 5, 16	San Juan	Metamorphic	--	4
142	Humble Oil and Refining Co.	Navajo D No. 1	T. 26 N., R. 19 W., sec. 30, 01	San Juan	Schist	--	4
143	Gulf Oil Corp.	Navajo BB No. 1	T. 26 N., R. 20 W., sec. 25, 02	San Juan	Chlorite schist	--	4
144	Amerada Hess Corp.	Navajo 4 No. 1	T. 27 N., R. 17 W., sec. 20, 03	San Juan	Granite	--	4
145	Sinclair Oil and Gas Co.	Navajo Tribal 141 No. 1	T. 27 N., R. 18 W., sec. 34, 13	San Juan	Granite	--	4
146	Northwest Pipeline Corp.	Barbara Kay No. 2	T. 27 N., R. 19 W., sec. 21, 02	San Juan	Unknown	Granite	5
147	Texaco Inc.	Navajo Tribe AS No. 1	T. 27 N., R. 19 W., sec. 28, 13	San Juan	Granite(?)	--	4
148	Texaco Inc.	Navajo Tribe AW No. 1	T. 27 N., R. 20 W., sec. 7, 09	San Juan	Metamorphic	--	4
149	Amerada Petroleum Corp.	Navajo No. 32–1	T. 28 N., R. 19 W., sec. 27, 13	San Juan	Granite	--	4
150	Humble Oil and Refining Co.	Navajo No. 2-1	T. 29 N., R. 15 W., sec. 18, 13	San Juan	--	--	--
151	Stanolind Oil and Gas Co.	USG No. 13	T. 29 N., R. 16 W., sec. 19, 07	San Juan	--	--	--
152	Amerada Petroleum Corp.	Navajo 20 No. 1	T. 29 N., R. 17 W., sec. 31, 04	San Juan	Granite	--	4
153	Pan American Petroleum Corp.	Hoover No. 1–A	T. 30 N., R. 16 W., sec. 23, 05	San Juan	--	--	--
154	Phillips Petroleum Co.	Navajo No. 1	T. 30 N., R. 17 W., sec. 5, 16	San Juan	Diorite?	--	4

No.	Company	Well name	Location	County	Description of Precambrian lithology from AMSTRAT log or other sources	Author's description of cuttings	Comment
			NEW MEXICO—Continued				
155	Sinclair Oil and Gas Co.	Navajo Tribal No. 4000–1	T. 30 N., R. 19 W., sec. 12, 11	San Juan	Diorite or gabbro	--	4
156	Pan American Petroleum Corp.	Navajo Tribal AD No. 1	T. 30 N., R. 21 W., sec. 13, 07	San Juan	Granite	--	4
157	Amoco Production Co.	Ute Mountain Gas Com D No. 1	T. 31 N., R. 14 W., sec. 10, 06	San Juan	--	--	--
158	Reynolds Mining Corp.	Chimney Rock No. 1	T. 31 N., R. 17 W., sec. 22, 06	San Juan	Quartzite	--	4
159	Humble Oil and Refining Co.	Navajo C No. 1	T. 31 N., R. 18 W., sec. 8, 01	San Juan	--	--	--
160	British American Oil Producing Co.	Navajo E No. 1	T. 31 N., R. 20 W., sec. 15, 06	San Juan	--	--	--
161	Texaco Inc.	Navajo AJ No. 1	T. 32 N., R. 18 W., sec. 35, 15	San Juan	Granite	--	4
162	Continental Oil Co.	Navajo 21 No. 1	T. 32 N., R. 19 W., sec. 21, 16	San Juan	--	--	--
163	Continental Oil Co.	South Ute Mountain No. 1	T. 32 N., R. 20 W., sec. 26, 03	San Juan	Granite	--	4
			UTAH				
164	Pan American Petroleum Corp.	USA Farnham Dome Unit No. 1	T. 15 S., R. 12 E., sec. 7, 13	Carbon	Metamorphic	--	4
165	Pan American Petroleum Corp.	USA Cullen No. 1	T. 15 S., R. 13 E., sec. 11, 16	Carbon	Granite	--	4
166	Mountain Fuel Supply Co.	Sunnyside Unit No. 1	T. 15 S., R. 13 E., sec. 17, 10	Carbon	Unknown	Granite	5
167	Arco Oil and Gas Co.	Chambers No. 1	T. 15 S., R. 13 E., sec. 28, 07	Carbon	Unknown	Granite	5
168	Texaco Inc.	Fence Canyon Unit No. 1	T. 15 S., R. 22 E., sec. 36, 09	Uintah	Unknown	Granite	5
169	Sinclair Oil and Gas Co.	Govt. San Arroyo No. 1	T. 16 S., R. 25 E., sec. 26, 06	Grand	Granite	--	4
170	Pure Oil Co.	Desert Lake Unit No. 1	T. 17 S., R. 10 E., sec. 1, 10	Emery	Granite gneiss	--	4
171	Pacific Natural Gas Exploration	Range Creek Unit No. 1–27	T. 17 S., R. 16 E., sec. 27, 06	Emery	Unknown	Quartz-biotite gneiss	5
172	Frontier Refining Co. - Stanolind	E.V. Crittendon No. 1	T. 17 S., R. 25 E., sec. 12, 16	Grand	Granite?	--	4
173	Lansdale	Federal No. 3–31	T. 17 S., R. 26 E., sec. 31, 08	Grand	Unknown	--	1
174	El Paso Natural Gas Co.	Pack Saddle No. 1	T. 18 S., R. 12 E., sec. 12, 08	Emery	Granite	--	4
175	Anschutz Corp.	State 411 No. 2	T. 18 S., R. 20 E., sec. 23, 05	Grand	Unknown	--	1
176	Reynolds Mining Corp.	Cedar Mountain Unit No. 1	T. 19 S., R. 12 E., sec. 29, 11	Emery	--	--	--
177	Humble Oil and Refining Co.	Woodside Unit (No. 4412) No. 1	T. 19 S., R. 13 E., sec. 12, 16	Emery	--	--	--
178	Union Oil of California; Continental Oil	Cisco Unit No. 1	T. 20 S., R. 21 E., sec. 23	Grand	Granite	--	4
179	American Metal Climax Inc.	Black Dragon Government No. 1	T. 21 S., R. 13 E., sec. 32, 09	Emery	Granite		4
180	Megadon Enterprises Inc.	Saleratus Federal State No. 2-36	T. 21 S., R. 14 E., sec. 36, 04	Emery	--	--	--
181	Superior Oil Co.	Grand Fault Unit No. 14–24	T. 21 S., R. 15 E., sec. 24, 13	Emery	--	--	--
182	Mobil Oil Corp.	Elba Flats Unit No. 1-30	T. 21 S., R. 22 E., sec. 30, 07	Grand	--	--	--
183	Equity Oil Co.	Government No. 1	T. 21 S., R. 23 E., sec. 20, 12	Grand	Granite	--	4
184	Three States Natural Gas Co.	Sinbad Unit No. 1	T. 22 S., R. 12 E., sec. 5, 03	Emery	Unknown	Granite	5
185	Reynolds Mining Corp.	Sinbad Unit No. 1	T. 22 S., R. 12 E., sec. 26, 02	Emery	--	--	--
186	Amax Petroleum Corp.	Green River Desert Unit No. 9–7	T. 22 S., R. 15 E., sec. 9, 07	Emery	--	--	--
187	Continental Oil Co.	Crescent Unit No. 1	T. 22 S., R. 20 E., sec. 17, 12	Grand	--	--	--
188	Amerada Petroleum Corp.	Sinbad Strat No. 1–354	T. 23 S., R. 10 E., sec. 28, 07	Emery	--	--	--
189	Standard Oil Co. of California	Unit No. 2	T. 23 S., R. 11 E., sec. 27, 04	Emery	Granite	--	4
190	Kerr McGee Oil Industries	TP Utah 27 No. 1	T. 23 S., R. 13 E., sec. 7, 08	Emery	--	--	--
191	Lion Oil Co. (Monsanto Chem. Co.)	Hatt Federal No. 1	T. 23 S., R. 14 E., sec. 19, 16	Emery	--	--	--
192	Shell Oil Co.	Chaffin Unit No. 1	T. 23 S., R. 15 E., sec. 21, 03	Emery	--	--	--
193	Mobil Oil Corp.	Jakey's Ridge No. 12-3	T. 23 S., R. 16 E., sec. 3, 05	Emery	--	--	--
194	Pan American Petroleum Corp.	Salt Wash No. 1	T. 23 S., R. 17 E., sec. 15, 12	Grand	--	--	--

195	Texaco Inc.	Government McKinnon No. 1	T. 23 S., R. 19 E., sec. 15, 13	Grand	--	--	--
196	Blackwood Nichols Co., Ltd.	San Rafael No. 1–28	T. 24 S., R. 10 E., sec. 28, 11	Emery	--	--	--
197	Superior Oil Co.	Iron Wash Unit No. 23-2	T. 24 S., R. 13 E., sec. 2, 11	Emery	--	--	--
198	Union Texas Petroleum	Federal Armstrong No. 1	T. 24 S., R. 14 E., sec. 10, 01	Emery	--	--	--
299	General Petroleum Corp.	Government No. 45–5 G	T. 24 S., R. 15 E., sec. 5, 11	Emery	--	--	--
200	Shell Oil Co.	Gruvers Mesa Federal No. 1	T. 24 S., R. 16 E., sec. 19, 07	Emery	--	--	--
201	Megadon Energy Corp.	Ten Mile No. 1–26	T. 24 S., R. 17 E., sec. 26, 13	Grand	--	--	--
202	Phillips Petroleum Co.	Onion Creek Unit No. 2	T. 24 S., R. 23 E., sec. 13, 07	Grand	--	--	--
203	Conoco Inc.	Conoco Federal No. 31-1	T. 24 S., R. 23 E., sec. 31, 10	Grand	--	--	--
204	Exxon Corp.	Onion Creek Federal No. 1	T. 24 S., R. 25 E., sec. 18, 05	Grand	--	--	--
205	Pan American Petroleum Corp.	USA Brown No. 1	T. 25 S., R. 12 E., sec. 24, 04	Emery	--	--	--
206	Union Oil Co. of California	Temple Wash Govt. 988 No. A–1	T. 25 S., R. 13 E., sec. 11, 04	Emery	--	--	--
207	Texaco Inc.	Temple Springs Unit No. 1	T. 25 S., R. 13 E., sec. 14, 04	Emery	--	--	--
208	Texaco Inc.	Temple Springs Unit No. 2	T. 25 S., R. 14 E., sec. 22, 14	Emery	--	--	--
209	Continental Oil Co.	Moonshine Wash Unit No. 2	T. 25 S., R. 15 E., sec. 22, 07	Emery	--	--	--
210	Superior Oil Co.	Bow Knot Unit No. 43–20	T. 25 S., R. 17½ E., sec. 20, 09	Grand	--	--	--
211	Tidewater Associated Oil	Flat Top Sweetwater No. 6–25	T. 26 S., R. 13 E., sec. 25, 12	Emery	--	--	--
212	Carter Oil Co.	Nequoia Arch Unit No. 3	T. 26 S., R. 14 E., sec. 26, 16	Emery	--	--	--
213	Davis Oil Co.	Pool Unit No. 1	T. 26 S., R. 17 E., sec. 17, 13	Emery	--	--	--
214	Pure Oil Co.	USA Mineral Point No. 1	T. 26 S., R. 18 E., sec. 7, 09	Grand	--	--	--
215	Southern Natural Gas Co.	Long Canyon Unit No. 1	T. 26 S., R. 20 E., sec. 9, 06	Grand	--	--	--
216	Texas Gulf Producing Co.	Federal No. 1–X	T. 26 S., R. 20 E., sec. 36, 09	Grand	--	--	--
217	Union Oil Co. of California	Burkholder Unit No. 1-G–1	T. 26 S., R. 22 E., sec. 1, 07	Grand	--	--	--
218	Carter Oil Co.	Blackburn Draw Unit No. 1	T. 27 S., R. 12 E., sec. 9, 01	Wayne	--	--	--
219	Superior Oil Co.	Hanksville Unit No. 31–30	T. 27 S., R. 13 E., sec. 30, 02	Wayne	--	--	--
220	Texaco Inc.	Nequoia Arch Unit No. 6	T. 27 S., R. 15 E., sec. 32, 08	Wayne	--	--	--
221	Superior Oil Co.	Horseshoe Canyon Unit No. 32–33	T. 27 S., R. 16 E., sec. 33, 07	Wayne	--	--	--
222	Southern Natural Gas Co.	USA No. 2	T. 27 S., R. 20 E., sec. 6, 11	San Juan	--	--	--
223	Megadon Energy Corp.	Lion Mesa No. 34–2	T. 27 S., R. 21 E., sec. 34, 11	San Juan	--	--	--
224	E.B. LaRue, Jr.	Government No. 1	T. 27 S., R. 22 E., sec. 15, 08	San Juan	--	--	--
225	Exxon Corp.	Gold Basin Unit No. 1	T. 27 S., R. 24 E., sec. 15, 04	San Juan	--	--	--
226	Murphy Corp.	Nequoia Arch Unit No. 4	T. 28 S., R. 14 E., sec. 14, 13	Wayne	--	--	--
227	Pan American Petroleum Corp.	Murphy Range Unit No. 1	T. 28 S., R. 18 E., sec. 12, 03	San Juan	--	--	--
228	Gulf Oil Corp.	Aztec Lockhart Federal No. 1	T. 28 S., R. 20 E., sec. 22, 12	San Juan	--	--	--
229	Pan American Petroleum Corp.	USA Lockhart No. 1	T. 28 S., R. 20 E., sec. 23, 16	San Juan	--	--	--
230	Richfield Oil Corp.	Hatch Mesa No. 1	T. 28 S., R. 21 E., sec. 22, 11	San Juan	--	--	--
231	Gulf Oil Corp.	Red Rock Unit No. 1	T. 28 S., R. 22 E., sec. 9, 02	San Juan	--	--	--
232	Gulf Oil Corp.	Hudson Wash Federal No. 1	T. 28 S., R. 22 E., sec. 34, 01	San Juan	--	--	--
233	Amerada Petroleum Corp.	Blue Mesa Unit No. 1	T. 29 S., R. 10 E., sec. 8, 13	Wayne	--	--	--
234	Tennessee Gas Transmission Co.	USA Sorrel Butte No. 1–A	T. 29 S., R. 12 E., sec. 33, 07	Wayne	--	--	--

No.	Company	Well name	Location	County	Description of Precambrian lithology from AMSTRAT log or other sources	Author's description of cuttings	Comment
			UTAH—Continued				
235	Phillips Petroleum Co.	Dirty Devil Federal No. 17–58–A	T. 29 S., R. 13 E., sec. 1, 01	Wayne	--	--	--
236	Continental Oil Co.	Hoover Federal No. 1	T. 29 S., R. 15 E., sec. 20, 08	Wayne	--	--	--
237	Humble Oil and Refining Co.	Rustler Dome No. 1	T. 29 S., R. 20 E., sec. 4, 12	San Juan	--	--	--
238	Husky Oil Co.	Federal No. 15–25	T. 29 S., R. 23 E., sec. 25, 15	San Juan	--	--	--
239	Superior Oil Co.	Horse Thief Canyon Unit No. 1–5	T. 29 S., R. 26 E., sec. 5, 16	San Juan	--	--	--
240	Reynolds Mining Corp.	Gibson Dome Unit No. 1	T. 29½ S. R. 20 E., sec. 35, 08	San Juan	--	--	--
241	Southland Royalty Co.	Burr Desert No. 1	T. 30 S., R. 12 E., sec. 24, 08	Wayne	--	--	--
242	Paradox Production; Putnam and Smoot	Federal No. 1	T. 30 S., R. 13 E., sec. 34, 02	Wayne	--	--	--
243	Phillips Petroleum Co.	French Seep No. 1	T. 30 S., R. 16 E., sec. 27, 06	Wayne	--	--	--
244	Pure Oil Co.	Lost Canyon No. 1	T. 30 S., R. 20 E., sec. 19, 15	San Juan	--	--	--
245	Apache Drilling Co.	Apache Lion Lisbon No. 1	T. 30 S., R. 23 E., sec. 13, 09	San Juan	--	--	--
246	Pure Oil Co.	Northwest Lisbon No. 1	T. 30 S., R. 24 E., sec. 10, 03	San Juan	--	--	--
247	Pure Oil Co.	NW Lisbon USA A No. 2	T. 30 S., R. 24 E., sec. 10, 09	San Juan	Granite	--	4
248	Kern County Land Co.; Skelly Oil	Crescent Creek No. 1–X	T. 31 S., R. 11 E., sec. 27, 16	Garfield	--	--	--
249	Superior Oil Co.	Utah Southern Government No. 22–19	T. 31 S., R. 15 E., sec. 19, 06	Garfield	--	--	--
250	Chorney Oil Co. et al	Hart Point Federal No. 1–22	T. 31 S., R. 22 E., sec. 22, 12	San Juan	--	--	--
251	Skelly Oil Co.	Church Rock Unit No. 1	T. 31 S., R. 23 E., sec. 26, 06	San Juan	--	--	--
252	Skelly Oil Co.	Summit Point No. 1	T. 31 S., R. 25 E., sec. 21, 13	San Juan	--	--	--
253	Lone Star Producing Co.	Federal Utah A No. 1	T. 31 S., R. 26 E., sec. 18, 02	San Juan	--	--	--
254	Texas Pacific Coal and Oil Co.	USA No. 1	T. 32 S., R. 15 E., sec. 33, 02	Garfield	--	--	--
255	Texas Co.	Cataract Canyon Unit No. 1	T. 32 S., R. 19 E., sec. 28, 10	San Juan	Unknown	Quartzite?	5
256	Southland Royalty Co.	Hog Canyon No. 1	T. 33 S., R. 13 E., sec. 8, 04	Garfield	--	--	--
257	Natomas North America Inc.	Redd Ranch No. 1–34A	T. 33 S., R. 20 E., sec. 34, 16	San Juan	--	--	--
258	Superior Oil Co.	Swap Mesa Unit No. 14–2	T. 34 S., R. 9 E., sec. 2, 13	Garfield	--	--	--
259	Midwest Exploration Inc.	Hughes No. 1	T. 34 S., R. 19 E., sec. 30, 12	San Juan	"Metamorphic" and schist	--	4
260	Skelly Oil Co.	Utah Federal C No. 1	T. 35 S., R. 15 E., sec. 4, 13	San Juan	--	--	--
261	Lemm and Maiatico	Dry Mesa Government No. 1	T. 35 S., R. 18 E., sec. 2, 13	San Juan	--	--	--
262	Phillips Petroleum Co.	Crittenden A No. 1	T. 35 S., R. 25 E., sec. 21, 10	San Juan	Granite	--	4
263	Gulf Oil Corp.	Coalbed Canyon Unit No. 2	T. 35 S., R. 26 E., sec. 20, 08	San Juan	--	--	--
264	Sinclair Oil and Gas Co.	McLane Federal No. 1	T. 36 S., R. 16 E., sec. 25, 01	San Juan	--	--	--
265	Southland Royalty Co.	Red Canyon No. 1	T. 37 S., R. 14 E., sec. 3, 11	San Juan	--	--	--
266	Kern County Land Co.	Moqui Federal No. 1–X	T. 37 S., R. 15 E., sec. 33, 03	San Juan	--	--	--
267	Edward J. Kubat	Government No. 1	T. 37 S., R. 19 E., sec. 23, 13	San Juan	--	--	--
268	Cities Service Oil and Gas Corp.	State A No. 1	T. 37 S., R. 23 E., sec. 32, 03	San Juan	--	--	--
269	Pan American Petroleum Corp.	Deadman Canyon Unit No. 1	T. 37 S., R. 24 E., sec. 20, 02	San Juan	--	--	--
270	Great Western Drilling Co.	Fish Creek No. 1	T. 38 S., R. 20 E., sec. 22, 04	San Juan	--	--	--
271	Ralph E. Fair	Butler Wash No. 1–A	T. 38 S., R. 21 E., sec. 16, 12	San Juan	--	--	--
272	Houston Oil and Minerals Corp.	Federal No. 11–6	T. 39 S., R. 14 E., sec. 6, 04	San Juan	--	--	--
273	Forest Oil Corp.	Government No. 1–31	T. 39 S., R. 15 E., sec. 31, 06	San Juan	--	--	--
274	Sinclair Oil and Gas Co.	Grand Gulch Federal No. 1	T. 39 S., R. 16 E., sec. 15, 15	San Juan	--	--	--

275	Carter Oil Co.	Government Hancock No. 1	T. 39 S., R. 17 E., sec. 26, 08	San Juan	--	--	--
276	Carter Oil Co.	Cedar Mesa Unit No. 1	T. 39 S., R. 18 E., sec. 15, 03	San Juan	--	--	--
277	Atlantic Refining Co.	Comb Wash Unit No. 1	T. 39 S., R. 20 E., sec. 14, 10	San Juan	--	--	--
278	Carter Oil Co.	Bluff Bench Unit No. 1	T. 39 S., R. 22 E., sec. 29, 12	San Juan	--	--	--
279	Shell Oil Co.	Bluff Unit No. 1	T. 39 S., R. 23 E., sec. 32, 02	San Juan	--	--	--
280	Reynolds Mining Corp.	Hatch Unit No. 1	T. 39 S., R. 24 E., sec. 4, 01	San Juan	--	--	--
281	Skelly Oil Co.	Nokai Unit No. 1–A	T. 40 S., R. 12 E., sec. 27, 04	San Juan	--	--	--
282	Utah Southern Oil Co.	Noble No. 1	T. 40 S., R. 18 E., sec. 28, 08	San Juan	Schist	Muscovite schist	5
283	Texaco Inc.	Navajo Tribe D No. 30	T. 40 S., R. 24 E., sec. 20, 03	San Juan	Metamorphic	Metasediments	5
284	Shell Oil Co.	Hovenweep No. 2	T. 40 S., R. 26 E., sec. 9, 15	San Juan	--	--	--
285	Service Oil Co.	Columbus Rexall No. 1	T. 41 S., R. 18 E., sec. 1, 01	San Juan	--	--	--
286	Texaco Inc.	Johns Canyon Unit No. 1	T. 41 S., R. 18 E., sec. 6, 13	San Juan	Granite	Granite	5
287	Utah Southern Oil Co.	Glockner Canyon No. 1	T. 41 S., R. 19 E., sec. 27, 15	San Juan	Unknown	--	2
288	Texaco Inc.	Navajo V No. 1	T. 41 S., R. 20 E., sec. 36, 04	San Juan	Metamorphic	Metasediments	5
289	Skelly Oil Co.	Mexican Hat No. 1	T. 42 S., R. 19 E., sec. 10, 15	San Juan	Quartzite	Metasediments	5
290	Gulf Oil Corp.	White Mesa No. 1	T. 42 S., R. 23 E., sec. 27, 01	San Juan	--	--	--
291	Pan American Petroleum Corp.	Navajo 161 No. 1	T. 43 S., R. 20 E., sec. 6, 14	San Juan	--	--	--
292	Cities Service Oil and Gas Corp.	Navajo B No. 1	T. 43 S., R. 20 E., sec. 36, 06	San Juan	--	--	--
293	Western Natural Gas Co.	English No. 1	T. 43 S., R. 22 E., sec. 22, 03	San Juan	--	--	--
294	Sunray DX Oil Co.	Utah Navajo B No. 1	T. 43 S., R. 23 E., sec. 4, 06	San Juan	--	--	--
295	Chuska Energy Co.	Copperhead 15–E No. 1	T. 43 S., R. 26 E., sec. 15, 05	San Juan	Unknown	--	1

APPENDIX 2—MEASURED SECTIONS USED AS CONTROL POINTS FOR MAPS AND CROSS SECTIONS

Number	Name of section	Location	County	Source of data
		COLORADO		
OC–1	None[1]	Sec. 25, T. 10 S., R. 102 W.	Mesa	Tweto (1979).
OC–2	None	Sec. 26, T. 12 S., R. 104 W.	Mesa	Tweto (1979).
OC–3	None	Sec. 19, T. 14 S., R. 100 W.	Mesa	Tweto (1979)
OC–4	Endlich Mesa	Sec. 11, T. 37 N., R. 7 W.	La Plata	Baars and Knight (1957).
OC–5	None	Sec. 20, T. 37 N., R. 7 W.	La Plata	Tweto (1979).
OC–6	None	Sec. 1, T. 37 N., R. 9 W.	La Plata	Tweto (1979)
OC–7	Rockwood Quarry	Sec. 12, T. 37 N., R. 9 W.	La Plata	Baars and Knight (1957).
OC–8	Stag Mesa	Sec. 19, T. 38 N., R. 7 W.	La Plata	Tweto (1979).
OC–9	None	Sec. 16, T. 38 N., R. 8 W.	La Plata	Tweto (1979).
OC–10	None	Sec. 7, T. 39 N., R. 8 W.	La Plata	Tweto (1979).
OC–11	Coalbank Pass	Sec. 29, T. 40 N., R. 8 W.	San Juan	Baars and Knight (1957).
OC–12	None	Sec. 33, T. 48 N., R. 14 W.	Montrose	Tweto (1979).
OC–13	None	Sec. 28, T. 49 N., R. 12 W.	Montrose	Tweto (1979).
OC–14	None	Sec. 5, T. 50 N., R. 14 W.	Mesa	Tweto (1979).
OC–15	None	Sec. 28, T. 51 N., R. 17 W.	Mesa	Tweto (1979).
		UTAH		
OC–16	None	Sec. 23, T. 20 S., R. 25 E.	Grand	Hintze (1980).
OC–17	None	Sec. 22, T. 22 S., R. 25 E.	Grand	Hintze (1980).

[1]Sections with no names are from the geologic maps of Utah and Colorado and are either spot elevations for the top of the Precambrian or are estimated thicknesses of strata above the Precambrian.

APPENDIX 3—DISCUSSION OF THE PRECAMBRIAN-CAMBRIAN CONTACT

I examined several outcrops on the south, west, and northwest sides of the Needle Mountains, Colorado, where the basal contact of the Ignacio is exposed. Features of the lower Ignacio Quartzite and underlying units are described following.

SOUTH OF MOLAS PASS

Along the trail south of Andrews Lake, just south of Molas Pass (sec. 26, T. 40 N., R. 8 W.), basement rocks are composed of Uncompahgre Formation, which consists of very indurated quartzite and minor slate beds. The clast-supported conglomerate beds of the Ignacio Quartzite are present as several large masses that are several tens of feet wide along strike and 50–60 ft or more thick. Beds dip steeply to the west. Clasts composing the conglomerate are mainly quartzite, apparently derived from the underlying Uncompahgre Formation, but also include dark metamorphic rock clasts and minor vein quartz (appendix fig. 1). Clast diameter ranges from 0.25 to 30 in.; clasts are angular to well rounded. Overall, clasts are less rounded than at other sections farther to the south. No systematic grading or imbrication was discerned at this outcrop. At this locality the conglomerate is overlain by Pennsylvanian carbonate rocks (J.A. Campbell, oral commun., 1994).

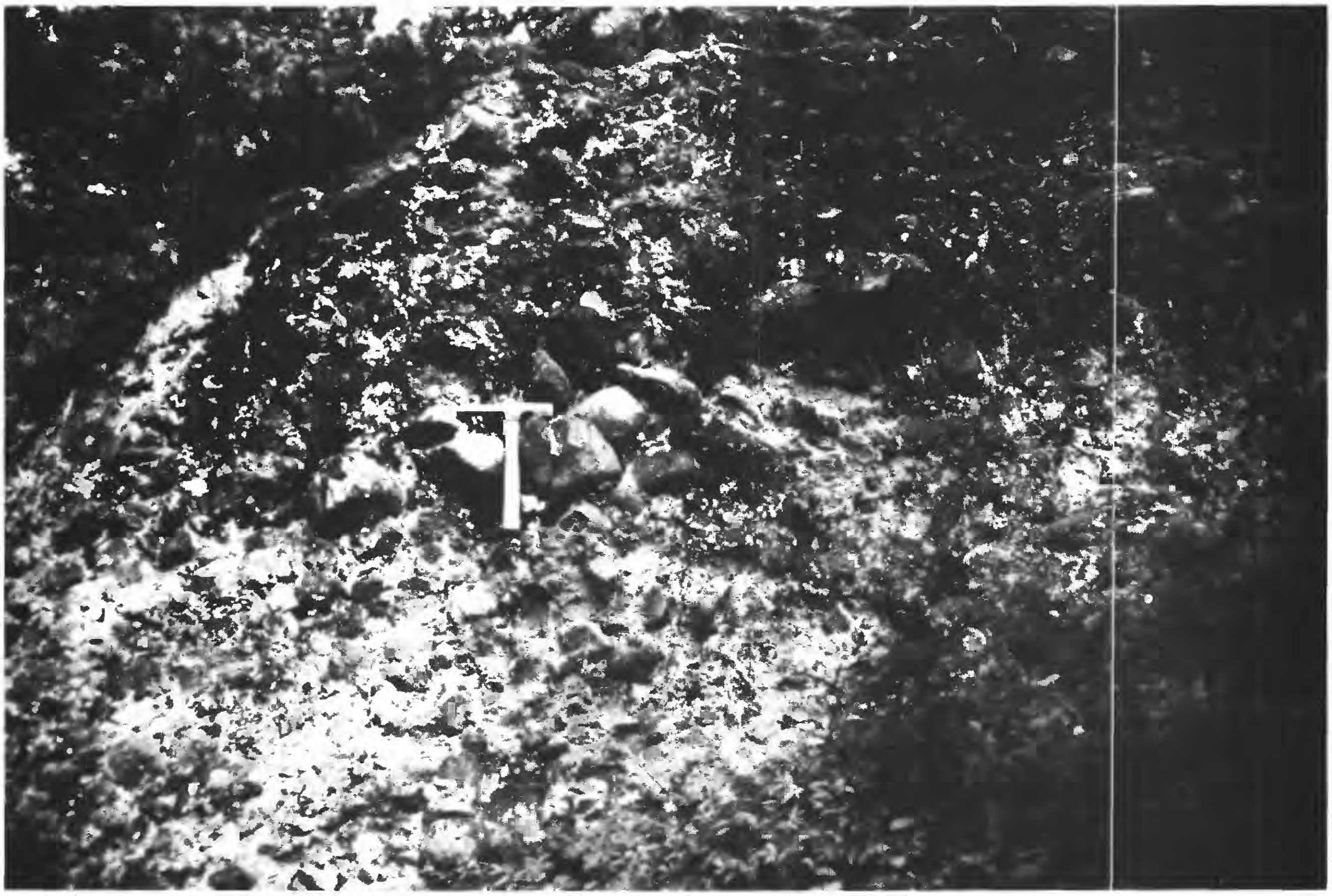
Appendix figure 1. Quartzite-clast conglomerate south of Andrews Lake. Note inclusion of clasts of other lithologies in addition to quartzite, large size of clasts, and degree of angularity of the clasts. Lens cap is 2.5 in. in diameter.

SOUTH FROM COAL BANK PASS

In this area, outcrops were studied from Coal Bank Pass southward about 1.25 mi to where the outcrops are again crossed by U.S. Highway 550 (sec. 31, T. 40 N., R. 8 W., sec. 6, T. 39 N., R. 8 W.). On the north side of Coal Bank Pass a major fault juxtaposes the Uncompahgre Formation against the Twilight Gneiss; fault movement is down to the north. The Ignacio Quartzite is underlain by Twilight Gneiss southward from Coal Bank Pass. On the north side of the parking area at the pass, quartzite at the base of the Ignacio directly overlies Twilight Gneiss; there was no basal conglomerate where the outcrop was examined, but small pebbles of quartz were observed dispersed in the lower few feet of Ignacio. This presents a problem for the model proposed by Baars and See (1968) because strata of the Ignacio adjacent to this fault should be full of talus debris.

In contrast, outcrops for about 0.5 mi south of the parking area contain many excellent examples of the basal quartzite conglomerate. In a few places outcrops of Twilight Gneiss are exposed beneath the conglomerate. The conglomerate is present as lenses as wide as about 30 ft and as thick as 15–20 ft, and dip is to the west. Abundant talus from overlying strata makes it difficult to tell if the lenses are separate or connected. Clasts in the conglomerate are mainly quartzite, derived from the Uncompahgre, but also include minor vein quartz. One clast of quartzite is split by a small vein of white quartz, indicating that the Uncompahgre could be the source for both types of clasts. No clasts of typical Twilight Gneiss lithology were seen. Clasts are as much as 24 in. in diameter, and most are oval and fairly well rounded (appendix fig. 2). The smaller clasts are more angular than the larger ones. In some outcrops there is some crude horizontal bedding and a sense of fining upward of clasts.

At one place along this line of outcrops a second type of conglomerate overlies the quartzite-clast conglomerate. This second type consists of mainly matrix supported vein-quartz clasts. Clast size is noticeably smaller than in the other conglomerate; the maximum diameter is about 3 in. The clasts in this conglomerate are angular to rounded, more angular than in the quartzite-clast conglomerate. At this location the vein-quartz conglomerate is in a 1-foot-thick lens that pinches out southward in a few feet; the northern end of the



Appendix figure 2. Quartzite-clast conglomerate south of Coal Bank Pass. Clasts here are smaller and more rounded than those at Andrews Lake. In addition, most clasts here are of Uncompahgre Formation quartzite. Hammer is 11 in. long.

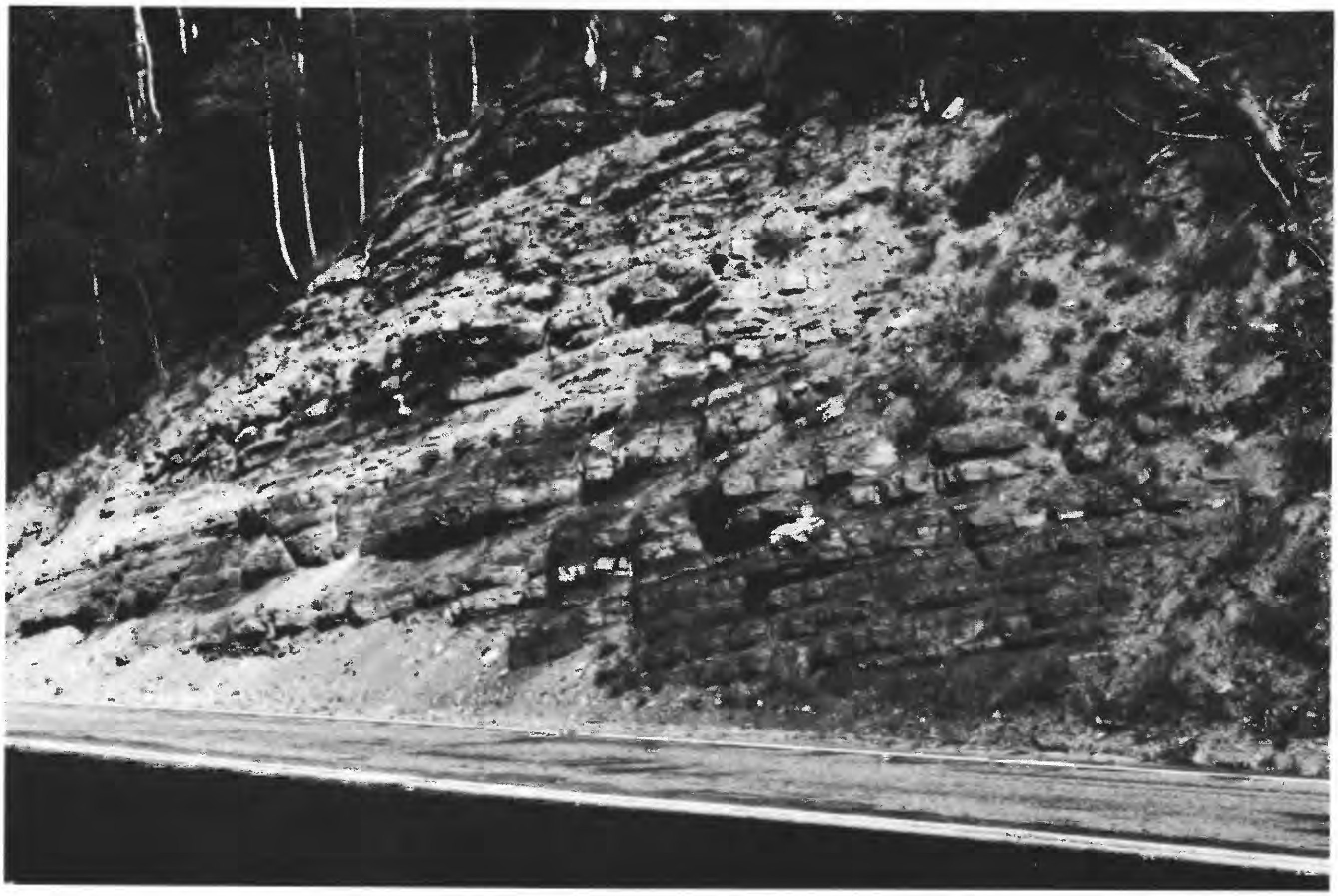
lens is covered. Above the conglomerates the Ignacio is composed of light-colored, fine- to coarse-grained, very well cemented sandstone (quartzite). The quartzite is in tabular beds from a few inches to about 2 ft in thickness; sedimentary structures include small-scale crossbeds and horizontal laminations.

The line of outcrops described above terminates temporarily where an old wagon road cuts up through the Ignacio from Mill Creek, below. At the point where the wagon road crosses the base of the Ignacio another example of the vein-quartz conglomerate overlying the quartzite-clast conglomerate is present. Exposures are poor, but two separate kinds of conglomerate can be discerned.

Farther to the south, past an area where no lower Paleozoic rocks are exposed, an example of the vein-quartz conglomerate is well exposed where Mill Creek crosses the outcrop (appendix fig. 3). At this location only a narrow, vertical sequence of the base of the Ignacio is exposed, and lateral relationships are generally covered. At the base of the section matrix-supported conglomerate is composed of vein-quartz clasts as much as 6 in. in diameter. No clasts of rounded Uncompahgre Formation were observed. Clasts are very angular and poorly sorted. The clasts gradually decrease in size both vertically and laterally at and near this section. Above the basal conglomerate the Ignacio is composed of brown to purple, thin-bedded muddy sandstone alternating with green and purple mudstone and shale. Small vertical trace fossils and mudcracks were seen in these beds. This sequence is well exposed in a road cut farther down the hill where Mill Creek is crossed by Highway 550 (appendix fig. 4). At this road cut the base of the Ignacio is covered, but the interbedded sandstone and shale sequence grades upward into quartzite. Rhodes and Fisher (1957) measured a section near this road cut and reported a basal quartz-pebble conglomerate in the Ignacio. They also recovered more than 200 inarticulate brachiopods from this locality.

ROCKWOOD QUARRY TO BAKERS BRIDGE

Basement rocks in the area from Rockwood Quarry to Bakers Bridge (secs. 12, 13, 24, T. 37 N., R. 9 W.) are composed of biotite granite named the Bakers Bridge Granite. The upper surface of the granite has relief on it, and a clast-supported quartzite conglomerate lies in low spots on this surface and partly pinches out on the flanks of high spots. This relationship is well exposed along the railroad



Appendix figure 5. Quartzite-clast conglomerate at Rockwood Quarry. Outcrop is along the railroad tracks just east of the quarry. Clast size here is smaller than at Andrews Lake or Coal Bank Pass, and clasts are more rounded that at the other locations. Hammer is 13 in. long.

Appendix figure 3 (facing page, top). Conglomerate composed of white vein quartz south of Coal Bank Pass. Clasts are smaller than 6 in. in diameter and are angular. Hammer is 11 in. long.

Appendix figure 4 (facing page, bottom). Sandstone, mudstone, and shale sequence in the lower part of the Ignacio Quartzite south of Coal Bank Pass where U.S. Highway 550 first crosses the Ignacio contact. Lower sequence grades upward into quartzite.

tracks just below Rockwood Quarry. At this location the conglomerate is composed of rounded clasts of Uncompahgre Formation quartzite as much as about 8 in. in diameter. The clast size is smaller on average and clasts are more rounded than at the Andrews Lake or Coal Bank Pass sections (appendix fig. 5). A lower lens of conglomerate pinches out against a small knob of Bakers Bridge Granite. Overlying the knob of granite is a coarse-grained sandstone that contains a few quartzite pebbles. This sandstone grades laterally and vertically into an upper quartzite-clast conglomerate bed. The combined lower and upper conglomerate beds are about 6–10 ft thick. Directly overlying the conglomerate are tabular beds of indurated sandstone that contain granules of feldspar. No pebbles of Uncompahgre Formation quartzite were observed in these overlying beds. A covered interval, suggesting shaly beds, overlies the lower quartzite interval of the Ignacio, and another quartzite sequence is present higher in the section.

Traveling southward from Rockwood Quarry on the east side of the railroad tracks, the Bakers Bridge Granite is exposed to the east of the highway and the Ignacio is exposed to the west, but the contact is obscured in most places. No conglomerates were observed in this area, although a basal quartzite bed of the Ignacio was observed to thin over a small knob of granite. Along this line of outcrops the combined Ignacio Quartzite and McCracken Sandstone Member of the Elbert forms a massive cliff of quartzite (appendix fig. 6). The lower part of this cliff is composed of poorly sorted sandstone that contains granules of potassium feldspar, white quartz, and gray quartz. The upper part of the cliff is composed of well-sorted, quartzose sandstone.

A little farther south, at Bakers Bridge, the cliff of quartzite has thinned considerably (appendix fig. 7). Feldspar-rich quartzite immediately overlies Bakers Bridge Granite. This outcrop has generated considerable controversy. For many years it was assumed that Cambrian Ignacio Quartzite overlies Bakers Bridge Granite at this location. Then, on the basis of gradational contact relations

Appendix figure 8. Mixed quartzite-clast and white vein-quartz-clast conglomerate south of Silverton, Colo. Most clasts are less than 3 in. in diameter. Lens cap is 2.5 in. in diameter.

Appendix figure 6 (facing page, top). Cliff of quartzite comprising the Ignacio Quartzite and the McCracken Sandstone Member of the Elbert Formation between Rockwood Quarry and Bakers Bridge. Cliff is approximately 100 ft high.

Appendix figure 7 (facing page, bottom). Cliff of quartzite at Bakers Bridge; person is standing on contact with Bakers Bridge Granite. Beds of quartzite lap out onto the right side of the granite knob. A few feet of Ignacio Quartzite may directly overly the granite. Quartzite cliff is 30–45 ft high.

with the overlying upper member of the Elbert Formation, Barnes (1954) interpreted the Ignacio as Devonian in age. Baars and Knight (1957) agreed with Barnes (1954) concerning the gradational contact with the upper member but concluded that the quartzite is the McCracken Sandstone Member of the Elbert not the Ignacio Quartzite. As of this writing J.A. Campbell (written commun., 1994) believes that there may be a thin bit of Ignacio present above the granite, but that most of the outcrop is McCracken. Based on the marked thinning of the quartzite between Rockwood Quarry and Bakers Bridge, it is reasonable that most or all of the Ignacio has lapped out depositionally onto a hill of Bakers Bridge Granite. The lower Paleozoic section dips into the subsurface a short distance south of Bakers Bridge, and field relations cannot be observed in that area.

SOUTH OF SILVERTON

Two sections were examined just off U.S. Highway 550 south of Silverton (sec. 30, T. 41 N., R. 7 W.). Basement rocks in this area are the Irving Formation. The section farthest to the south is composed of matrix-supported clasts of quartzite from the Uncompahgre Formation and also of white vein quartz (appendix fig. 8). Maximum observed clast size is about 6 in., and the clasts are angular to subangular. The outcrops are poorly exposed, but crude horizontal bedding probably is present.

Conglomerate is also present just to the north of the previous location, in an area where a mineralized fault in the Irving and Ignacio has been prospected. Much of this section has been disturbed by mining activities, and only general characteristics of the Ignacio could be recorded. The total section of quartzite is quite thick, 100 ft or more, and a thick section of white vein-quartz conglomerate is at the base. Clasts are relatively small, generally less than 2–3 in.

Appendix figure 9. Cliff of Ignacio Quartzite and possibly McCracken Sandstone Member on the east side of Endlich Mesa. Eolus Granite underlies the cliff; upper surface of the granite is deeply weathered and forms a slope. Muddy sandstone bed in Ignacio that weathers to a recess is about 1 ft thick. Lower part of quartzite (in foreground) is about 20 ft thick.

in diameter, and are angular to subangular. Quartz pebbles are present well into the overlying quartzite, not just restricted to the base. No quartzite pebbles from the Uncompahgre Formation were seen at this section.

ENDLICH MESA

A final section was examined at Devon Point on Endlich Mesa (sec. 1, 12, T. 37 N., R. 7 W.). This location was described by Cross (1904). The basement rock is Eolus Granite. Although the Ignacio is very well exposed in a vertical cliff (appendix fig. 9), its contact with the Eolus is difficult to get to in most places. Where examined, at the north end of this outcrop, the top of the granite is deeply weathered, producing a red slope that appears from a distance to be shale. No conglomerate was seen at the base of the Ignacio, although the whole formation is full of granules (as much as 0.25 in. in diameter) of potassium feldspar and white and gray quartz. The granules are concentrated on bedding planes, and the rest of the unit is well-sorted quartzite. There is a slight amount of very subtle channeling or undulation at the base of the Ignacio. Several mudstone interbeds are in the quartzite; the thickest one is about 1 ft thick (appendix fig. 9). These interbeds are persistent laterally along strike. The thickness of the quartzite was previously measured as 52 ft (Cross, 1904) and 87 ft (Baars and Knight, 1957). No McCracken Sandstone Member was differentiated in these previous reports, although Baars and Knight (1957, p. 117) stated that both units should be present in this area. Quartzite is also present within the dolomite of the overlying upper member of the Elbert Formation. The stratigraphically higher quartzite is nearly identical to that of the underlying Ignacio Quartzite and includes granules of quartz but does not include granules of feldspar. Although no basal conglomerate was observed at this location, Campbell (1994) reported thick, channel-like conglomerates just to the southeast that are composed of clasts of Vallecito Conglomerate.

DISCUSSION

Conglomerates at the contact between Proterozoic rocks and Cambrian rocks can usually be divided into two types: (1) those composed of mainly quartzite clasts and

(2) those composed of white vein-quartz clasts. Although all the exposed outcrops of this contact were not examined, some generalizations can be made.

Conglomerates of the first type commonly are lenticular bodies; some pinch out laterally onto knobs of basement rock. Clasts are mainly of quartzite that is identical to that of the Uncompahgre Formation or of the Vallecito Conglomerate. Clasts of other lithologies are present, however, in the Andrews Lake area. Although white vein quartz is present in almost all the sections examined, it is normally a minor constituent of the quartzite-clast conglomerate. The main exception to this trend is at one of the sections just south of Silverton. At this section vein-quartz clasts, as well as quartzite clasts, are very abundant. Clast diameter ranges from granules to 30 in. or more; the largest clasts are in the Andrews Lake area. Clasts decrease in size both to the north and south of Andrews Lake. Rounding of clasts increases to the south. In the Coal Bank Pass area some fining upward of clasts is visible, but in general the quartzite conglomerates are very poorly sorted.

Two modes of deposition have been proposed for these quartzite conglomerates: (1) "talus-like" deposits (Baars and See, 1968) and (2) proximal braided stream deposits (Campbell, 1994a, b). Although Baars (1966) and Baars and See (1968) made many astute observations regarding the quartzite conglomerates, certain features lead me to question the association of the conglomerates with adjacent fault scarps in Late Cambrian time. Campbell (1994a, b) noted that the conglomerates bear little relation to faults in the Needle Mountains area. One of the major faults is at Coal Bank Pass, yet the conglomerate at this location pinches out before reaching the fault and clasts in this area are well rounded, indicating transport, probably by fluvial processes. I observed present-day talus and fluvial deposits in areas where the Uncompahgre Formation crops out and noted that clasts of talus deposits are very angular, unlike clasts in the quartzite conglomerates. Cobbles and boulders of Uncompahgre are rounded, however, after a short amount of rolling in the Animas River. Another important fact is that none of the pebbles or cobbles of Uncompahgre clasts are incorporated into the basal quartzite beds of the Ignacio; instead, clasts are restricted to the conglomerate beds. This suggests to me that the conglomerates were not deposited as part of the same depositional system as the overlying quartzite but were probably already lithified prior to deposition of the Ignacio.

Campbell (1994a, b) suggested that the conglomerates are significantly older than the Ignacio Quartzite and are late Precambrian or early Cambrian in age. He proposed a series of braided streams draining a weathered Precambrian terrane southwestward from the Transcontinental arch. Because clasts in these conglomerates are composed primarily of Uncompahgre Formation quartzite and because the Uncompahgre is only known from the immediate Needle Mountains area, it seems reasonable to assume that the clasts had a local source. Fault-induced topography, as proposed by Baars (1966) and Baars and See (1968), may have produced the boulders that eventually ended up in the conglomerate; however, this process probably occurred earlier than the Late Cambrian, possibly in the late Precambrian.

Conglomerates of the second type, consisting of fairly small, angular, white vein-quartz clasts, are younger than conglomerates of the first type. Where examined, outcrops were not well enough exposed to be sure about the geometry of these conglomerates. In two places south of Coal Bank Pass the conglomerates have a thin, lensoid geometry. At other locations vein-quartz clasts are concentrated at the base of the section, but clasts are dispersed both vertically and laterally into adjacent beds. Clasts at all sections are quite angular, and no trends in clast size between locations were noted. Clasts decrease in size upward at one section south of Coal Bank Pass. An important point is that these vein-quartz conglomerates grade laterally and vertically into the thin-bedded sandstone, shale, and quartzite of the Ignacio Quartzite.

The origin of the vein-quartz clasts is not known, but quartz veins are present in many of the Proterozoic rocks of the area, including the Irving Formation, Twilight Gneiss, and Uncompahgre Formation. In many places quartz veins have weathered essentially in place and the ground is littered with quartz clasts similar to those within the Ignacio Quartzite. Another common feature of basal Ignacio beds is an abundance of potassium feldspar grains. The combination of the vein-quartz clasts and feldspar grains suggests to me that Late Cambrian seas transgressed over a surface of low relief on Precambrian rocks. This surface probably was deeply weathered, especially in the granitic terranes, and the accumulated grus was reworked and incorporated into the Ignacio. In some places the quartz clasts were apparently reworked into lenticular deposits, possibly in tidal channels whereas in other places the clasts were widely dispersed, possibly in tidal flat or beach environments.

Campbell (1994a, b) made an important distinction between the two types of conglomerates in the Ignacio Quartzite. Based on my observations of the units, I agree that the older conglomerate probably is the product of fluvial processes, not fault-scarp talus deposition. The older conglomerate probably has little, if anything, to do with deposition of the Ignacio. The younger conglomerate probably is the product of a marine transgression over a weathered Precambrian surface.

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