Burial and Thermal History of the Paradox Basin, Utah and Colorado, and Petroleum Potential of the Middle Pennsylvanian Paradox Formation

By Vito F. Nuccio *and* Steven M. Condon

EVOLUTION OF SEDIMENTARY BASINS—PARADOX BASIN
A.C. Huffman, Jr., Project Coordinator

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CONTENTS

PLATES

FIGURES

TABLES

BURIAL AND THERMAL HISTORY OF THE PARADOX BASIN, UTAH AND COLORADO, AND PETROLEUM POTENTIAL OF THE MIDDLE PENNSYLVANIAN PARADOX FORMATION

By Vito F. Nuccio *and* Steven M. Condon

ABSTRACT

The Ismay–Desert Creek interval and Cane Creek cycle of the Alkali Gulch interval of the Middle Pennsylvanian Paradox Formation in the Paradox Basin of Utah and Colorado contain excellent organic-rich source rocks having total organic carbon contents ranging from 0.5 to 11.0 percent. The source rocks in both intervals contain types I, II, and III organic matter and are potential source rocks for both oil and gas. Organic matter in the Ismay–Desert Creek interval and Cane Creek cycle of the Alkali Gulch interval (hereinafter referred to in this report as the “Cane Creek cycle”) probably is more terrestrial in origin in the eastern part of the basin and is interpreted to have contributed to some of the gas produced there.

Thermal maturity increases from southwest to northeast for both the Ismay–Desert Creek interval and Cane Creek cycle, following structural and burial trends throughout the basin. In the northernmost part of the basin, the combination of a relatively thick Tertiary sedimentary sequence and high basinal heat flow has produced very high thermal maturities. Although general thermal maturity trends are similar for both the Ismay–Desert Creek interval and Cane Creek cycle, actual maturity levels are higher for the Cane Creek due to the additional thickness (as much as several thousand feet) of Middle Pennsylvanian section.

Throughout most of the basin, the Ismay–Desert Creek interval is mature and in the petroleum-generation window (0.10 to 0.50 production index (PI)), and both oil and gas are produced; in the south-central to southwestern part of the basin, however, the interval is marginally mature (<0.10 PI) for petroleum generation, and mainly oil is produced. In contrast, the more mature Cane Creek cycle contains no marginally immature areas—it is mature (>0.10 PI) in the central part of the basin and is overmature (past the petroleum-generation window (>0.50 PI)) throughout most of the eastern part of the basin. The Cane Creek cycle generally produces oil and associated gas throughout the western and central parts of the basin and thermogenic gas in the eastern part of the basin.

Burial and thermal-history models were constructed for six different areas of the Paradox Basin. In the Monument upwarp area, the least mature part of the basin, the Ismay–Desert Creek interval and Cane Creek cycle have thermal maturities of 0.10 and 0.20 PI and were buried to 13,400 ft and 14,300 ft, respectively. A constant heat flow through time of 40 mWm^{-2} (milliwatts per square meter) is postulated for this area. Significant petroleum generation began at 45 Ma for the Ismay–Desert Creek interval and at 69 Ma for the Cane Creek cycle.

In the area around the confluence of the Green and Colorado Rivers, the Ismay–Desert Creek interval and Cane Creek cycle have thermal maturities of 0.20 and 0.25 PI and were buried to 13,000 ft and 14,200 ft, respectively. A constant heat flow through time of 42 mWm^{-2} is postulated for this area. Significant petroleum generation began at 60 Ma for the Ismay–Desert Creek interval and at 75 Ma for the Cane Creek cycle.

In the area around the town of Green River, Utah, the Ismay–Desert Creek interval and Cane Creek cycle have thermal maturities of 0.60 and greater and were buried to 14,000 ft and 15,400 ft, respectively. A constant heat flow through time of 53 mWm^{-2} is proposed for this area. Significant petroleum generation began at 82 Ma for the Ismay–Desert Creek interval and at 85 Ma for the Cane Creek cycle.

Around Moab, Utah, in the deeper, eastern part of the basin, the Ismay–Desert Creek interval and Cane Creek cycle have thermal maturities of 0.30 and around 0.35 PI and were buried to 18,250 ft and 22,000 ft, respectively. A constant heat flow through time of 40 mWm^{-2} is postulated for this area. Significant petroleum generation began at 79 Ma for the Ismay–Desert Creek interval and at 90 Ma for the Cane Creek cycle.

At Lisbon Valley, also in the structurally deeper part of the basin, the Ismay–Desert Creek interval and Cane Creek cycle have thermal maturities of 0.30 and greater than 0.60 PI and were buried to 15,750 ft and 21,500 ft, respectively. A constant heat flow through time of 44 mWm^{-2} is postulated for this area. Significant petroleum generation began at 79 Ma for the Ismay–Desert Creek interval and at 100 Ma for the Cane Creek cycle.

The area around Hermosa, Colo., in the southeastern part of the basin, has experienced a shallower burial history than the other areas in the basin, yet it has one of the highest thermal maturities. Here, the Ismay–Desert Creek interval and Cane Creek cycle have vitrinite reflectance values of 1.58 and 1.63 percent and were buried to 13,700 ft and 15,500 ft, respectively. Due to Tertiary igneous activity in this part of the basin, a variable heat flow is proposed: from 600 to 30 Ma, 45 mWm^{-2}; from 30 to 25 Ma, 63 mWm^{-2}; and from 25 Ma to present, 50 mWm^{-2}. Significant petroleum generation began at 72 Ma for the Ismay–Desert Creek interval and at 76 Ma for the Cane Creek cycle.

INTRODUCTION

During Pennsylvanian time, the Paradox Basin of Utah and Colorado was a rapidly subsiding northwest-trending trough that was filled with sequences of organic-rich shale, limestone, dolomite, anhydrite, halite, and siliciclastic deposits. Although only a minor percentage of the stratigraphic section in the Paradox Basin comprises dark-colored, organic-rich shale, the shales are of great importance due to their petroleum-generation potential. The term “shale” is somewhat misleading because these beds consist of more than 30 percent carbonate, 20–30 percent fine-grained quartz, and 40–50 percent clay and kerogen (Montgomery, 1992). Total organic carbon (TOC) values for these black shales of from less than 0.5 percent to more than 11.0 percent make them excellent petroleum source rocks. The black shales were deposited during transgressive phases in basin development and have produced in excess of 400 million barrels of oil and 1 trillion cubic feet (TCF) of gas (Baars and Stevenson, 1982; Hite and others, 1984). Generally, petroleum accumulations are stratigraphic traps in (1) carbonate rocks that are interbedded with the shales and (2) older (Mississippian) carbonates that are in fault contact with the shales. Recently, fractured, organic-rich shales, such as in the Cane Creek cycle of the Paradox Formation, have become an attractive petroleum play in the basin.

In this study we address three critical, interrelated factors that have controlled the generation, distribution, and accumulation of petroleum from the Paradox Formation in the Paradox Basin: (1) structural and burial history of the basin, (2) regional thermal-maturity trends, and (3) quality and distribution of source rocks throughout the basin. The burial history of stratigraphic units was determined by the structural evolution of the basin, and thermal maturity trends closely follow burial trends. Similarly, the petroleum-generation history of source rocks in the Paradox Formation is directly related to both the burial and thermal regimes throughout the basin.

The structural and burial history of the Paradox Basin is illustrated using a series of isopach maps for Cambrian through Jurassic rocks. Geohistory curves illustrate the burial history for the entire stratigraphic section (Cambrian through Tertiary) for six different locations in the basin. The variation in the thermal history of the basin is illustrated using maturity maps (constructed using production index (PI) and vitrinite reflectance (R_o) values) on two stratigraphic and potential source-rock intervals, the Ismay–Desert Creek interval and the Cane Creek cycle of the Paradox Formation. The type, quantity, and quality of organic matter in these two source rocks are presented, and the petroleum potential is discussed. Finally, using models that incorporate hydrocarbon-generation kinetics, we demonstrate that the timing of petroleum generation, accumulation, and destruction within the Paradox Formation has been a function of the source rock and the structural, burial, and thermal history of the basin.

Acknowledgments.—We thank Charles E. Barker and Bonnie L. Crysdale for their help in collecting core and cutting samples and for data used for source-rock evaluation. Ted Daws analyzed hundreds of samples for Rock-Eval pyrolysis. Additional Rock-Eval pyrolysis data provided by Michele Tuttle of the U.S. Geological Survey and Mark Richardson of Exxon Production and Research were very useful and greatly appreciated. We also acknowledge the Utah Geological Survey for their interest in the project and their assistance in identifying wells and providing samples for us to collect. Critical review by Karen Franczyk and Ben Law greatly added to the quality of the manuscript. Finally, we thank Project Chief, Curt Huffman, and all people associated with the Evolution of Sedimentary Basins–Paradox Basin Project for their helpful discussions and suggestions.

GEOGRAPHIC AND STRUCTURAL SETTING

The Paradox Basin (fig. 1) is an oval area in southeastern Utah and southwestern Colorado that is defined by the maximum extent of salt in the Middle Pennsylvanian Paradox Formation (Hite and others, 1984). 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 was primarily a Pennsylvanian and Permian feature that accumulated thick deposits of carbonate, halite, and clastics in response to tectonic downwarping and simultaneous uplift along its northeastern border. 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 downcutting by the Colorado River and its tributaries.

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

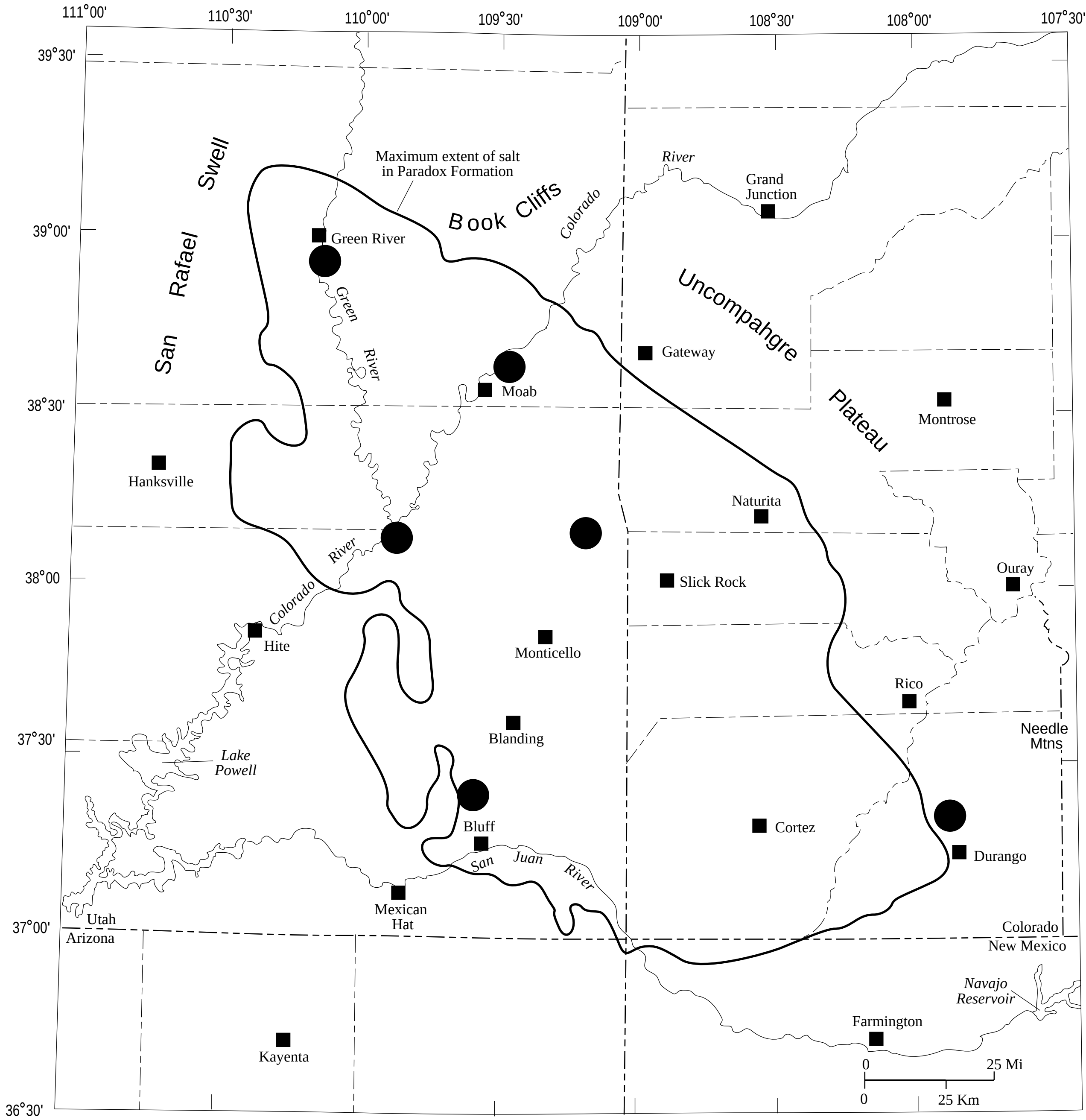


Figure 1. Location map of the Paradox Basin. Large dots indicate areas where burial, thermal, and petroleum-generation histories were reconstructed.

are widely exposed. The southeast 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 ill-defined topographically and structurally; it extends northwestward from the Four Corners (the junction of Utah, Colorado, New Mexico, and Arizona) to the Henry Basin across the Monument upwarp. The northwest 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.

The structure and physical features of the Paradox Basin within the area defined by the salt (figs. 1, 2) are also very diverse. The northern part of the basin has been termed the Paradox fold and fault belt (Kelley, 1958a). This area consists of a series of roughly parallel, northwest-trending faults, anticlines, and synclines. The northeastern part of this area is more complexly folded, with piercement of some anticlines by salt from the Paradox Formation. Dissolution of salt along the crests of some anticlines in this region has caused downfaulting and the development of grabens at the crests. Rocks as old as Pennsylvanian are exposed in the

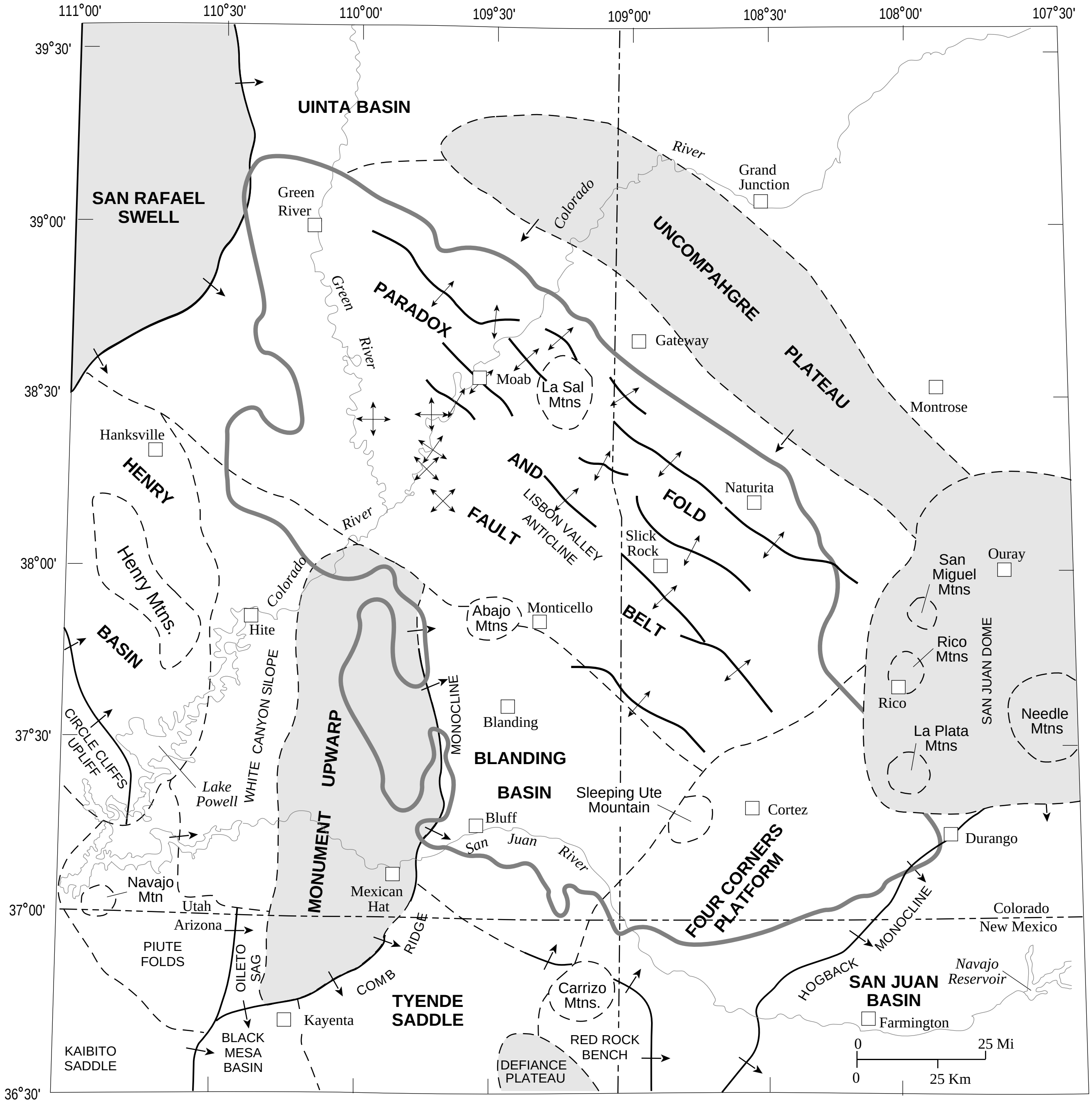


Figure 2. Map showing structural elements of the Paradox Basin and adjacent areas. Modified from Kelley (1958a, 1958b).

cores of some of the anticlines, and remnants of Cretaceous rocks are present in some synclines and in collapsed blocks within the anticlines. The southwestern part of this basin subdivision is also folded and faulted 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 its surface.

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 areas for which southeast 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.

Also 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 intrusions are Late Cretaceous to Tertiary in age and deformed the enclosing sedimentary rocks into broad domes.

STRATIGRAPHY

Sedimentary rocks of the Paradox Basin overlie an Early Proterozoic basement of metamorphic gneiss and schist that is locally intruded by granite. An Early and Middle Proterozoic sedimentary unit, the Uncompahgre Formation, is present in the southeastern part of the basin (Tweto, 1987). A possibly Middle to Late Proterozoic sequence of metasedimentary rocks is present in the western and southern parts of the basin.

Cambrian through Jurassic strata unconformably overlie the basement rocks in much of the basin. Remnants of Cretaceous rocks are also present, especially in the southeastern part of the basin, but, except for the igneous intrusive centers, Tertiary rocks have been completely eroded away. Data are complete enough to construct isopach maps for Cambrian through Jurassic units, which have been combined into three groups: sub-Pennsylvanian, Pennsylvanian and Permian, and Triassic and Jurassic.

SUB-PENNSYLVANIAN ROCKS

In pre-Pennsylvanian 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. Cambrian through Devonian sedimentation west of this line was in a deep miogeocline that encompassed western Utah, eastern Nevada, and adjacent areas. Sedimentation east of the Wasatch line was on a stable shelf in mainly shallow marine conditions (Poole and others, 1992). The structural setting changed in the latest Devonian and Mississippian when the Antler orogeny uplifted a north-trending highland in Nevada and adjacent areas, resulting in terriginous clastic influx into adjacent basins (Poole and Sandberg, 1991). The Paradox Basin was far east of the orogenic belt and remained a shallow-marine shelf during the Late Devonian and Mississippian. Many of the sub-Pennsylvanian units have correlatives in central Colorado and northwestern New Mexico, indicating that the shelf conditions extended some distance eastward from the Paradox Basin.

Sub-Pennsylvanian rocks consist of the Lower and Middle Cambrian Tintic Quartzite, Upper Cambrian Ignacio Quartzite, Middle Cambrian Ophir Formation (or Shale), Middle Cambrian Maxfield Limestone, Middle(?) and Upper Cambrian Lynch Dolomite, Upper Devonian Aneth and Elbert Formations and Ouray Limestone, and the Mississippian Leadville Limestone. Correlative units, whose names originated in the Grand Canyon area, are the Lower Cambrian Tapeats Sandstone, Middle Cambrian Bright Angel Shale and Muav Limestone, and Mississippian Redwall Limestone (fig. 3). An isopach of sub-Pennsylvanian units shows those units thickening uniformly westward except for an area near the Four Corners (fig. 4). This interval ranges in thickness from about 300 ft to about 2,600 ft. The thicknesses of individual formations are shown in figure 3.

The Tapeats, Ignacio, and Tintic each consist of a basal conglomerate overlain by silica-cemented sandstone and minor shale beds. The conglomerates were deposited by streams that filled in depressions on the Precambrian erosion surface. The middle and upper parts of each unit were deposited in a shallow-marine environment by a sea that transgressed from the miogeocline to the west. The Ophir and Bright Angel Shales are mixtures of sandstone, limestone, and shale. They represent deeper water sedimentation during the continuation of the Cambrian marine transgression. The Maxfield and Muav Limestones and Lynch Dolomite are carbonates deposited on the relatively stable cratonic shelf on the margin of the continent (Lochman-Balk, 1972).

Rocks of Ordovician, Silurian, and Early and Middle Devonian age are not recognized in the Paradox Basin. It is possible that thin accumulations of at least part of this sequence were deposited in the basin, but post-Cambrian erosion may have removed all traces of them.

Upper Devonian rocks were also deposited in shallow-marine conditions on the cratonic shelf (Baars, 1972; Poole and others, 1992). The Aneth Formation consists of black shale and dolostone deposited in euxinic conditions. The Aneth is recognized only in a relatively small area in the southern part of the basin. It may have been more widespread, but a sea-level drop and accompanying erosion prior to deposition of the overlying Elbert Formation would have removed the Aneth from most of the basin.

Low to moderately elevated uplands in central Colorado shed clastic debris into the basin that was reworked into the McCracken Sandstone Member of the Elbert Formation. The McCracken is recognized in most of the basin. The upper member of the Elbert is a dolostone and shale unit that includes intervals of sandstone in its lower part. In some exposures in Colorado, the Elbert contains salt hoppers, indicating evaporitic, subaerial conditions. Devonian fish remains have been found in the upper member as well as in the McCracken Sandstone Member and the Aneth Formation. The upper member is recognized in all parts of the basin.

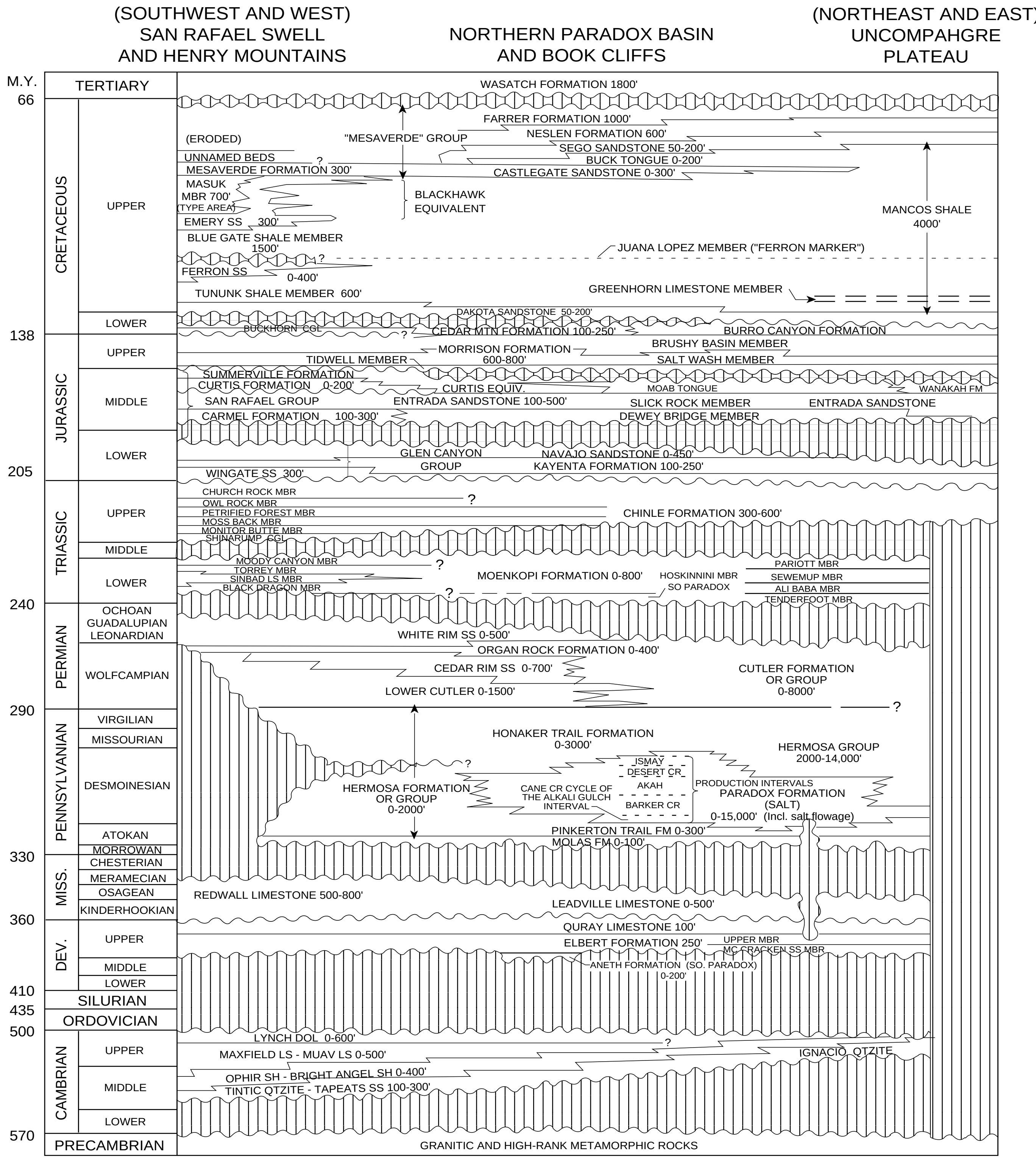


Figure 3. Correlation chart for rocks of the Paradox Basin and vicinity. Modified from Molenaar (1987).

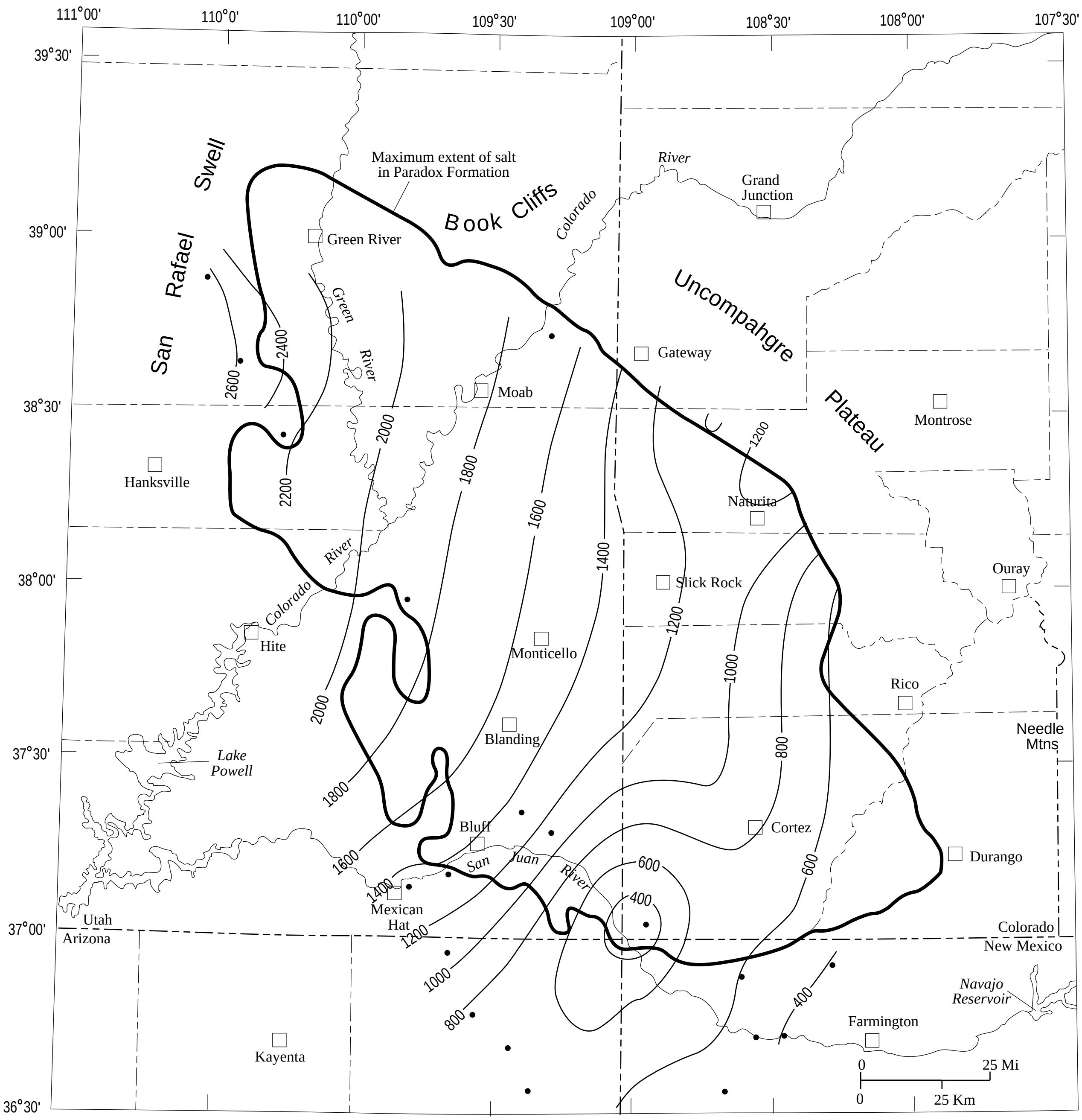


Figure 4. Isopach map of sub-Pennsylvanian stratigraphic units in the Paradox Basin. Contour interval 200 ft.

The uppermost Devonian unit in the basin is the Ouray Limestone. The Ouray is a carbonate unit deposited in a warm, shallow-water marine environment. It contains beds of dolostone and intervals of green shale in some areas. The Ouray is thin but extensive and is present in all parts of the basin.

Sea-level fall after deposition of the Ouray ended the Devonian Period. There is some evidence of exposure of the Ouray surface to subaerial erosion (Armstrong and Mamet, 1977), but there was not enough erosion to remove the Ouray in most places. Renewed transgression of the sea from the west initiated deposition of the Mississippian Leadville and Redwall Limestones. These units formed during a series of transgressive and regressive events that were affected by the Antler orogeny. Irregularities on the sea floor, possibly caused in part by tectonics, led to development of a wide variety of depositional subenvironments and a corresponding diversity of fauna.

A final sea-level fall in the Late Mississippian exposed the carbonates of the Leadville and Redwall to a subaerial environment. A regolith developed on this surface, as well as solution cavities and karst topography in some areas. This residual deposit is considered to be a part of the overlying Lower and Middle Pennsylvanian Molas Formation.

PENNSYLVANIAN AND PERMIAN ROCKS

The collision of the Laurentia and Gondwana supercontinents in the Pennsylvanian and Permian (Scotese and McKerrow, 1990) had a profound effect on the area of the Paradox Basin. During this time, the Uncompahgre Plateau experienced rapid and large-scale uplift, and the adjacent northeastern side of the Paradox Basin subsided. All Cambrian through Mississippian rocks were stripped from the plateau, as was an unknown thickness of Precambrian rock. Sediments of great thickness (as much as 12,000 ft) accumulated in the trough just to the southwest of the Uncompahgre Plateau during the Pennsylvanian and Permian (fig. 5). Subsidence was less southwest of a line extending from the San Rafael Swell through the confluence of the Green and Colorado Rivers to about the Cortez, Colo., area. In this area, as much as about 4,000 ft of sediment accumulated during the Pennsylvanian and Permian,

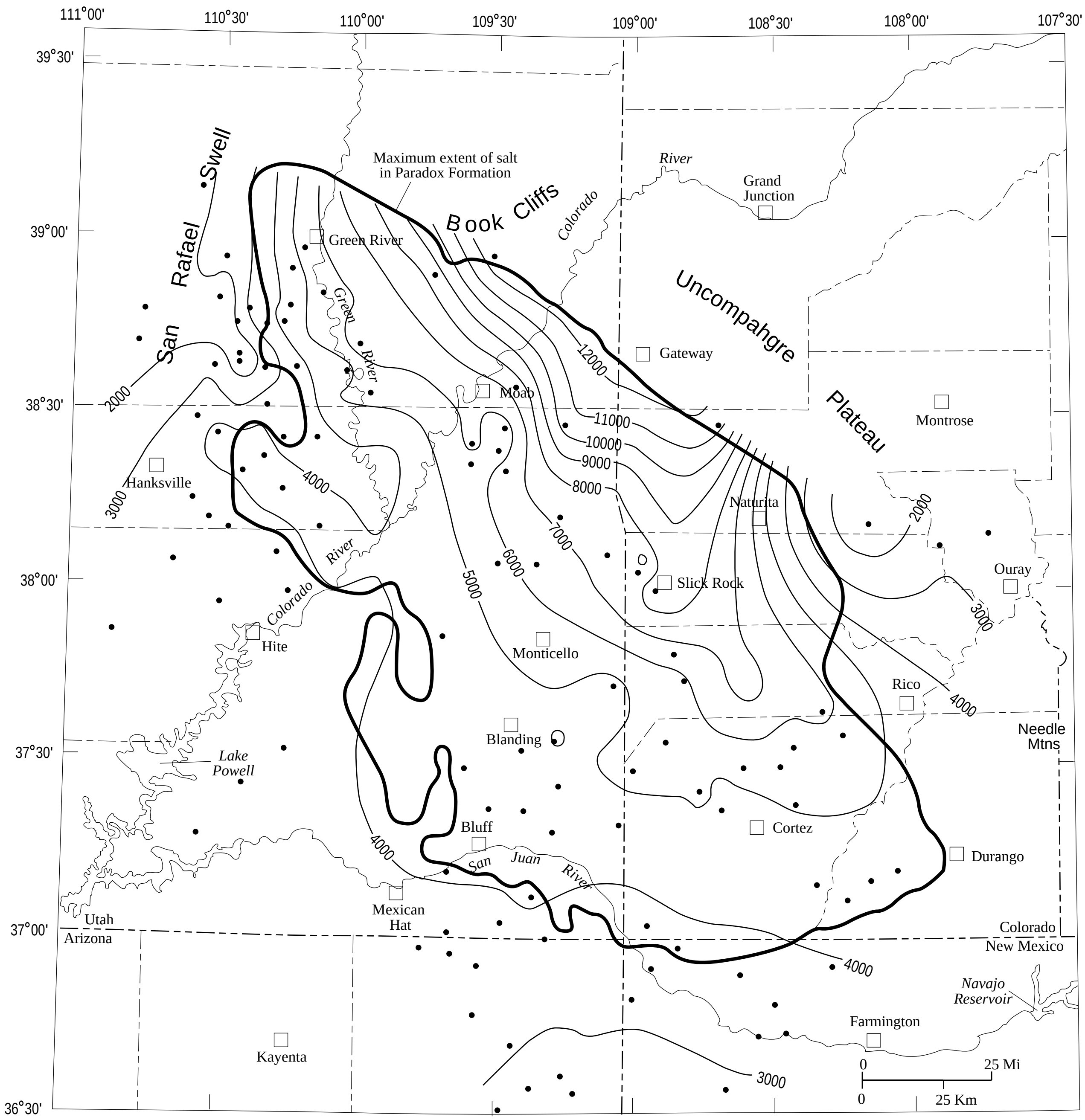


Figure 5. Isopach map of Pennsylvanian and Permian stratigraphic units in the Paradox Basin. Contour interval 1,000 ft.

although this is only about one-third as much as accumulated in the deepest part of the basin.

Deposits within the oldest Pennsylvanian formation, the Molas Formation, are transitional from nonmarine to marine. The lower part of the Molas may have begun forming in Mississippian time as a residual deposit on the exposed carbonate surface of the Leadville and Redwall Limestones. The middle part of the Molas was deposited and reworked by streams. The upper part has, in addition to fluvial strata, marine limestone beds deposited by the transgressing Middle Pennsylvanian sea.

The Middle and Upper Pennsylvanian Hermosa Group makes up most of the Pennsylvanian rocks in the basin. The Hermosa includes, from oldest to youngest, the Middle Pennsylvanian Pinkerton Trail and Paradox and the Middle and Upper Pennsylvanian Honaker Trail Formations (Wengerd and Matheny, 1958). The Pinkerton Trail consists of interbedded marine limestone and dark shale. It was deposited in shallow-marine conditions of normal salinity.

The Paradox Formation is a very diverse unit composed of dolostone, black shale, anhydrite, halite, and other salts. Halite is the most abundant constituent of the Paradox, occurring in beds tens of feet thick. Black dolomitic shale is also an important rock type because it is the source of some of the oil and gas recovered in the Paradox Basin. Many of the samples used for this study are from the black shales of the Paradox. The Paradox was deposited in a series of cycles (Hite and Buckner, 1981) that represent repeated desiccation and marine flooding of the basin. In the southwestern part of the basin, the Paradox grades into shelf carbonates, including algal-mound buildups that act as petroleum reservoirs. In the easternmost part of the basin, the Paradox cannot be differentiated, and the undivided Hermosa contains abundant clastic material that was shed from the Uncompahgre Plateau; this clastic material is interbedded with carbonate (Franczyk, 1992).

The black shales of the Paradox have been used as marker beds to correlate depositional cycles throughout the basin. The cycles have been grouped into larger zones, “substages” (Baars and others, 1967) (fig. 3), or “production intervals” (Hite and others, 1984) (fig. 3). For this study, maturity maps were prepared for the Ismay and Desert Creek production intervals and for the Cane Creek cycle, which is in the upper part of the Alkali Gulch production interval of the Paradox Formation (fig. 3).

The Honaker Trail Formation is composed of cyclically deposited limestone, sandstone, and shale. It represents a return to normal marine conditions in contrast to the evaporitic marine conditions of the Paradox Formation. In addition, the Honaker Trail contains significant eolian and fluvial strata, especially on the northeastern side of the basin.

Continued uplift of the Uncompahgre Plateau in Late Pennsylvanian and Early Permian time eventually unroofed the Precambrian basement rocks. The Cutler Formation is mostly a product of this unroofing process and consists of arkose, sandstone, and relatively minor amounts of mudstone. The Cutler was deposited in a series of alluvial fans that were transporting material southwestward (Campbell, 1980). The Cutler is commonly viewed as a Lower Permian unit; however, it cannot be dated precisely because the fluvial strata composing it are nonfossiliferous. Intertonguing relations of fluvial strata of the Cutler with underlying carbonates of the Hermosa Group suggest that the Cutler is in part Pennsylvanian (Wengerd and Matheny, 1958).

In the northwestern and southwestern parts of the Paradox Basin, the Cutler is raised to group status and includes the Elephant Canyon Formation or the Halgaito Formation, the Cedar Mesa Sandstone, the Organ Rock Formation, and the White Rim Sandstone or the De Chelly Sandstone (Baars, 1962). The southwestward transition of arkosic redbeds of the undifferentiated Cutler into lighter colored sands of the Cedar Mesa is evident at about the confluence of the Green and Colorado Rivers (fig. 1).

The Elephant Canyon Formation is recognized in the northwestern part of the basin. It is a mixed marine and nonmarine unit containing limestone beds interbedded with marine sandstone as well as with fluvial and eolian strata. The Elephant Canyon grades southward into the Halgaito Formation, a redbed unit exposed along the San Juan River in southeastern Utah. The Halgaito consists of sabkha sandstone as well as minor fluvial sandstone and mudstone.

The Cedar Mesa Sandstone is composed of thick sandstone beds separated by thin silty sandstone and limestone beds. It is mainly an eolian dune deposit but includes interdune and thin playa facies. In the vicinity of the Comb Ridge monocline in the southern part of the basin, the Cedar Mesa grades eastward into an evaporite facies of interbedded sandstone, shale, and gypsum.

The Organ Rock Formation is another redbed unit, composed mostly of sandstone and siltstone. Much of the unit was deposited in sabkha environments; however, in places, it contains significant amounts of eolian strata. The Organ Rock thins and pinches out westward on the San Rafael Swell.

The uppermost units of the Cutler Group are the correlative White Rim Sandstone and De Chelly Sandstone. The White Rim is in the northwestern part of the basin and pinches out southward and eastward at about the Colorado River. The De Chelly Sandstone is present in large areas in northeastern Arizona and northwestern New Mexico but only extends a short distance northward into the area of the Paradox Basin. It pinches out before merging with the White Rim. Both the White Rim and De Chelly are eolian deposits composed almost entirely of sandstone.

The youngest Permian unit in the basin is the marine Kaibab Limestone (Lower Permian). The western side of the basin is at the eastern depositional edge of the Kaibab. Erosion in latest Permian and earliest Triassic time left only remnants of the Kaibab on the San Rafael Swell and in scattered subsurface areas along the western side of the basin. It is a marine deposit.

TRIASSIC AND JURASSIC ROCKS

In the Triassic and Jurassic, sedimentation in the area of the Paradox Basin was influenced to a great degree by development of magmatic arcs to the south and west of the current basin (Dickinson, 1989). Development of the arcs had the effect of periodically uplifting source areas and providing sediment to the Western Interior, including the area of the Paradox Basin. Triassic and Jurassic sedimentary units contain large volumes of ash derived from volcanic activity in the arcs. Times of less tectonic activity, especially in the Middle Jurassic, led to deposition of marine, sabkha, and eolian deposits.

Western and southwestern source areas are indicated by the thickness patterns displayed by Triassic and Jurassic units (fig. 6). In general, the combined units thin uniformly from west-southwest to the east-northeast in the study area. An exception is in the northern part of the basin (fig. 6). This thick area is probably due to the influence of salt tectonics.

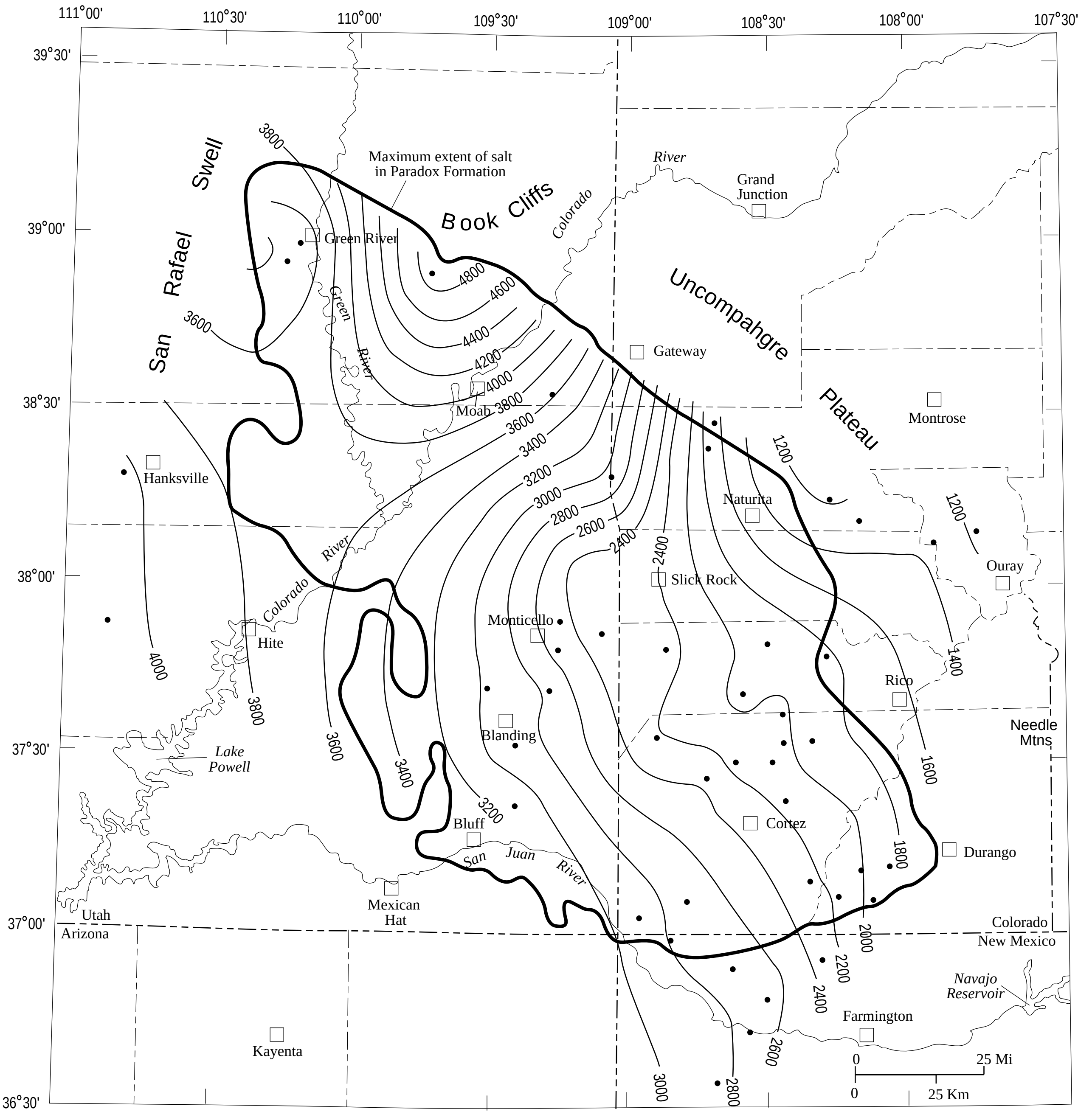


Figure 6. Isopach map of Triassic and Jurassic stratigraphic units in the Paradox Basin. Contour interval 200 ft.

Deposition of Permian, Triassic, and Jurassic sediment onto thick sequences of salt in the Middle Pennsylvanian Paradox Formation led to the diapiric rise of the salt in several anticlines in the fold and fault belt (fig. 2). When the salt moved up into the anticlines, it moved out of the synclines, forming sediment traps. Individual Triassic and Jurassic units have been shown to thin on the flanks of anticlines and to thicken in the synclines (Cater, 1970).

The basal Triassic unit in the basin is the Moenkopi Formation of Early and Middle(?) Triassic age. The Moenkopi has been divided into several members with different names in various parts of the basin (fig. 3). In the western part of the basin, lower beds of the Moenkopi are fluvial strata shed eastward from a highland west of the Paradox Basin area (Huntoon, 1992; Huntoon and others, 1994). Younger members of the Moenkopi are a combination of sabkha, mudflat, and fluvial deposits, and one marine limestone unit, the Sinbad Limestone Member (fig. 3). A combination of erosion in the Middle Triassic and, possibly, nondeposition led to absence of the Moenkopi in parts of southeastern Utah and most of southwestern Colorado (Stewart and others, 1972a).

Uplift south of the study area in Late Triassic time led to development of a northwestward-flowing fluvial system in the lower part of the Upper Triassic Chinle Formation (Dubiel, 1989). Other components of the Chinle fluvial system had sources in the Uncompahgre Plateau. The Chinle has also been divided into several members in various parts of the basin (Stewart and others, 1972b) (fig. 3). In southwestern Colorado, a correlative unit is known as the Dolores Formation. The Chinle and Dolores are mostly redbed units that were deposited in fluvial, lacustrine, sabkha, and eolian environments.

Previously, the contact between Triassic and Jurassic strata was thought to be gradational and to lie within the Glen Canyon Group (Harshbarger and others, 1957). Pipiringos and O’Sullivan (1978) have, however, interpreted the contact at the top of the Chinle to be an unconformity and the Triassic-Jurassic boundary to lie at that unconformity.

The oldest Jurassic unit is the Lower Jurassic Glen Canyon Group, which is composed of the Wingate Sandstone, Kayenta Formation, and Navajo Sandstone. The Wingate and Navajo are massive eolian units, and the Kayenta is fluvial. Contacts between formations of the group are gradational; an unconformity is at the top of the Navajo Sandstone. The Navajo was removed by pre-Middle Jurassic erosion in the northeastern part of the study area. The Navajo contains local limestone beds that are as thick as 10 ft. These limestones were deposited in interdune playas and are associated with fossil trees, dinosaur footprints, and invertebrate remains.

Unconformably overlying the Glen Canyon Group is the Middle Jurassic San Rafael Group, named for exposures on the San Rafael Swell (Gilluly and Reeside, 1928). The San Rafael Group consists of the Page Sandstone, Carmel Formation, Entrada Sandstone, Curtis Formation, and the Summerville Formation (west) or Wanakah Formation (east). These formations were deposited in and on the margins of an inland sea that transgressed from the north during at least two transgressive-regressive cycles.

The Page Sandstone is an eolian deposit that had previously been included with the Navajo Sandstone but that was distinguished by Peterson and Pipiringos (1979). It is conformably overlain by the Carmel Formation, a marine limestone, sandstone, and shale. The Carmel is overlain, in part, by the Entrada Sandstone, but near the Green River, Wright and others (1962) interpreted the Carmel to change facies eastward to a sabkha deposit, which they included as the lowest member of the Entrada Sandstone. In the San Rafael Swell, the Entrada is a silty sandstone, probably deposited in or near shallow water. Eastward, the Entrada changes to an eolian deposit; near Moab, an upper eolian member, the Moab Tongue, is recognized.

There was apparently a fall in sea level after deposition of part of the Entrada, followed by another cycle of transgression during which the marine Curtis Formation was deposited. The fall in sea level is inferred from the presence of an unconformity between the Entrada and Curtis (Pipiringos and O’Sullivan, 1978). The Curtis consists of fossiliferous limestone, sandstone, and shale that unconformably overlies the main body of the Entrada. The Curtis changes facies eastward and pinches out between the Green and Colorado Rivers beneath the Moab Tongue of the Entrada. In the western part of the basin, the Summerville Formation, a sabkha deposit, conformably overlies the Curtis.

In the eastern part of the basin, the Wanakah Formation overlies and, in part, grades laterally into the Entrada Sandstone. In Colorado, the Wanakah includes a limestone and gypsum unit, the Pony Express Limestone Member, at the base. The upper part of the Wanakah consists of sandstone and shale redbeds that have been interpreted to partly grade into the Entrada Sandstone (O’Sullivan, 1980). Upper beds of the Wanakah are correlative with beds of the Summerville Formation.

The Upper Jurassic Morrison Formation is the youngest Jurassic unit in the basin. In many places there is an unconformity separating the Morrison from underlying Middle Jurassic strata. The Morrison was deposited in a variety of depositional environments, ranging from eolian to fluvial and lacustrine. In the southern part of the basin, the lowest member of the Morrison is the Bluff Sandstone Member. This member was deposited in an eolian erg and is partly equivalent to the Junction Creek Sandstone of southwestern Colorado (Condon, 1992). Much of the Morrison is composed of fluvial sandstone and mudstone that have sources to the west and southwest of the basin (Peterson and Turner-Peterson, 1987). An upper member, the Brushy Basin Member, was deposited in a combination of lacustrine and marginal lacustrine environments (Turner and Fishman, 1991).

The contact between the Morrison Formation and overlying strata has been the subject of much discussion. In the northwestern part of the basin, the overlying unit is the Lower Cretaceous Cedar Mountain Formation, whereas in the southeast, a correlative unit is the Lower Cretaceous Burro Canyon Formation. The contact between these units and the Morrison was interpreted to be a disconformity (Young, 1960); however, Tschudy and others (1984) indicated that the Cedar Mountain and Burro Canyon may be a continuation of deposition of the Morrison Formation. Recent studies by Aubrey (1992) also suggest interfingering between the Morrison and overlying units.

CRETACEOUS AND TERTIARY ROCKS

Late Tertiary to Holocene erosion removed Cretaceous and Tertiary rocks throughout most of the Paradox Basin. In order to reconstruct the burial history of the region, we assume that similar thickness and lithology trends of Cretaceous and Tertiary strata from areas around the periphery of the basin (such as the Henry Basin, Book Cliffs, and the Mesa Verde National Park area) can be extrapolated across the Paradox Basin.

The Cedar Mountain and Burro Canyon Formations of Early Cretaceous age overlie the Morrison Formation. The Cedar Mountain is recognized in areas west of the Colorado River and the Burro Canyon in areas to the east (Molenaar, 1981). Many of the mesas in the eastern and southern parts of the basin are capped by the Burro Canyon. The Cedar Mountain and Burro Canyon Formations, comprising conglomeratic sandstone beds and mudstone, are mostly fluvial and flood plain in origin. The Cedar Mountain was derived from areas to the west, whereas the Burro Canyon was derived from areas to the south and southwest of the Paradox Basin (Molenaar, 1981). The thickness of the Cedar Mountain and Burro Canyon ranges from 50 to 200 ft.

The Upper Cretaceous Dakota Sandstone unconformably overlies the Cedar Mountain and Burro Canyon Formations. The Dakota is a coastal-plain unit deposited in front of the advancing Mancos sea (Molenaar, 1981). It comprises, in ascending order, conglomeratic channel sandstone, dark-gray carbonaceous shale, coal, and, in places, a marine sandstone. Regionally, the Dakota is about 200 ft thick.

Conformably overlying the Dakota is the Upper Cretaceous Mancos Shale. The Mancos was deposited in the Western Interior Cretaceous seaway and is primarily composed of uniform, dark-gray mudstone, shale, and siltstone. The Mancos ranges in thickness from about 3,500 ft in the Book Cliffs area to about 2,000 ft in southwestern Colorado (Molenaar, 1981).

The Upper Cretaceous Mesaverde Group is partially preserved in only a few areas in the Paradox Basin; however, it is fully preserved in the Book Cliffs area in the northern part of the basin and in the Mesa Verde National Park area southeast of Cortez, Colo. (Molenaar, 1981). The Mesaverde gradationally overlies the Mancos Shale and consists of marginal-marine sandstones, coastal- or delta-plain paludal carbonaceous shale and coal with channel sandstones, and alluvial or upper delta plain noncarbonaceous shales and channel sandstones (Molenaar, 1981).

In the Mesa Verde area, the group is divided into three formations: in ascending order, the Point Lookout Sandstone, the Menefee Formation, and the Cliff House Sandstone. The total thickness of the Mesaverde in this area is about 900 ft; it thins to the northeast and thickens to the southwest. In the Book Cliffs area, the Mesaverde Group is divided into, in ascending order, the Castlegate Sandstone, Sego Sandstone, and Neslen, Farrer, and Tuscher Formations (Fisher and others, 1960; Molenaar, 1981) (fig. 3). The combined thickness of the Mesaverde Group and the intertonguing Buck Tongue of the Mancos Shale in this area is about 2,300 ft.

The dominant event of latest Cretaceous and Tertiary time was the development of uplifts and adjacent basins associated with the Laramide orogeny. Major structural features in the Paradox Basin region are the Uncompahgre Plateau, San Rafael Swell, Monument upwarp, San Juan dome, and Uinta Basin (fig. 2). Records of Tertiary sedimentation in the Paradox Basin are absent due to late Tertiary uplift and erosion; however, it is very likely that Paleocene, Eocene, and possibly even Oligocene, Miocene, and Pliocene rocks were once present in the northernmost part of the basin (Robinson, 1972; McDonald, 1972).

The North Horn Formation is Maastrichtian to late Paleocene in age (Spieker, 1949; Robinson, 1972; Fouch, 1976; Fouch and others, 1983) and comprises a series of interbedded sandstone, conglomerate, shale, and limestone. The thickness of the North Horn is highly variable throughout central and eastern Utah, ranging from 500 ft to more than 3,800 ft. The North Horn is thought to have once been present as far south as lat 39°N. and covered much of the northern part of the Paradox Basin (Robinson, 1972).

Eocene rocks once present in the northern Paradox Basin probably include the Wasatch, Green River, and Uinta Formations (Robinson, 1972). The Wasatch Formation is composed of silty, micaceous, and calcareous shale that grades into mudstone and fine- to medium-grained sandstone. The Green River Formation comprises organic-rich, laminated shale; sandstone; siltstone; silty shale; and oolitic, algal, and ostracodal limestone. The lithology of the Uinta Formation is extremely variable, including boulder conglomerate, sandstone, siltstone, and limestone. These combined Eocene strata extended southward to around lat 38°30′N., likely covering the northern part of the Paradox Basin (Robinson, 1972). Eocene rocks in the northern Paradox Basin area could have been as thick as 1,000–2,000 ft (McDonald, 1972).

Volcanic activity during Oligocene through Pliocene time undoubtedly contributed to the rock column in the

Paradox Basin. Igneous intrusions in the area include the La Sal, Henry, Abajo, and San Juan Mountains. Ash and flows likely covered much of southwestern Colorado and southeastern Utah and may have been as thick as 1,000 ft.

METHODS

The isopach maps prepared for this report were constructed from a database of about 200 well logs from oil and gas test wells in the Paradox Basin. The geophysical logs were checked against sample logs prepared by the American Stratigraphic Company (AMSTRAT), and correlations were made from one log to another. Thickness files were then generated and were gridded and contoured using a program called Interactive Surface Modeling (ISM), a product of Dynamic Graphics, Inc. The area shown on the contour maps was divided into a grid of 300 rows and 300 columns, equivalent to a grid size in the *x* direction (longitude) of about 0.75 mi and in the *y* direction (latitude) of about 0.9 mi. Each grid node was calculated by considering the eight closest control points.

Source rock characterization of 107 shale samples from the Ismay–Desert Creek interval and Cane Creek cycle was performed using Rock-Eval pyrolysis analysis. Rock-Eval pyrolysis is used to evaluate rapidly the petroleum-generation potential of rocks, and it provides information on the quantity, type, and thermal maturity of the organic matter in a rock. Pyrolysis is the heating of organic matter in the absence of oxygen to yield organic compounds. Complete details of the Rock-Eval pyrolysis technique and associated problems are given in Espitalie and others (1977) and Peters (1986). Most of the Ismay–Desert Creek and Cane Creek samples used in this study were taken from a larger set of samples from several stratigraphic units (Cretaceous through Mississippian) throughout the Paradox Basin (Barker, Nuccio, and others, in press). Barker, Szmajter, and others (in press) statistically analyzed this same larger data set and interpreted the petroleum potential for various source rocks.

The Rock-Eval pyrolysis technique yields several measurements that determine the thermal maturity and hydrocarbon generation potential of source rocks (table 1). Total organic carbon content (TOC) is a useful parameter for evaluating the quantity of organic matter in a potential source rock. Total organic carbon was determined using the Rock-Eval II instrument and is the sum of the carbon in the pyrolyzate plus the carbon from the residual oxidized organic matter. In general (depending on the type of organic matter and lithology), and for this study, fine-grained rocks having a total organic carbon content of greater than 0.50 percent are considered a potential hydrocarbon source rock. Interpretation of the total organic carbon content and source rock potential of the Paradox Formation samples is presented in a later section.

Other Rock-Eval measurements include the S1 peak, which is the amount of hydrocarbons that are thermally distilled from the rock; the S2 peak, the amount of hydrocarbons generated by pyrolytic degradation of the kerogen; and the S3 peak, the amount of carbon dioxide (in milligrams) generated during heating to 390°C.

Rock-Eval pyrolysis also measures T_{max}, the temperature at which the S2 peak occurs; that is, the temperature of maximum hydrocarbon yield. T_{max} can be used as a thermal maturity indicator because the temperature for maximum hydrocarbon yield increases as kerogen matures. Hydrocarbons begin to be generated between T_{max} values of 435°C and 440°C, and thermal cracking to gas and condensate occurs at about 460°C (Tissot and Welte, 1984).

The hydrogen index (HI) is defined as the S2 yield (remaining hydrogen-generating capability of the organic matter) normalized by the total organic carbon content (TOC); in other words, the fraction of the total organic carbon that is generated as hydrocarbons. The hydrogen index is also useful in describing the type of organic matter present in the source rock, as will be discussed in a later section on source rock potential. The oxygen index (OI) is the quantity of carbon dioxide from the S3 peak normalized by the total organic carbon content and, if plotted against the HI, yields information about the type of organic matter in the source rock.

The production index (PI), or transformation ratio, is defined as the ratio S1/(S1 + S2), or the ratio of volatile hydrocarbon yield to total hydrocarbon yield. The production index can be used to evaluate thermal maturity because, if there is no migration of hydrocarbons, it increases with heating. In general, the beginning of generation is at a production index of about 0.08–0.10, and thermal cracking of oil to gas and condensate occurs at about production indices of 0.40–0.50.

In addition to T_{max} and PI values, vitrinite reflectance (R_o) was also used to define levels of thermal maturity for some of the shale samples (table 2). Vitrinite, a maceral derived from woody plant material, is common in coal and organic-rich shale. Vitrinite reflectance is a measure of the proportion of light reflected from a polished vitrinite grain. It is related to the degree of metamorphism of the vitrinite grain and can be related to other thermal maturity indicators. Thirty-five samples of shale from the Paradox Formation were analyzed for vitrinite reflectance (table 2). The samples were prepared by crushing, mounting in epoxy on a microscope slide, planing off when hardened, and polishing. The mean random vitrinite reflectance (from randomly oriented indigenous vitrinite grains) was determined using plane-polarized incident white light and a 546-nm monochromatic filter, in immersion oil, on a reflected light microscope with a nonrotating stage (Bostick, 1979; Bustin, 1986).

Vitrinite reflectance values have been correlated with oil and gas generation for potential source rocks (Dow, 1977; Waples, 1985). For example, Waples (1985) stated that, depending on the type of kerogen, oil generation begins over a range of R_o values—onset of oil generation ranges from

Table 1. Rock-Eval pyrolysis data, Paradox Formation, Paradox Basin, Utah and Colorado.

[Location given as section-township-range. T_{max} is temperature at which maximum yield of hydrocarbons occurs during pyrolysis; S1 is integral of first peak (existing hydrocarbons volatized at 250°C for 5 minutes); S2 is integral of second peak (hydrocarbons produced by pyrolysis of solid organic matter between 250° and 550°C); S3 is integral of third peak (CO_2 produced by pyrolysis of kerogen between 250° and 390°C); PI, production index (S1/S1+S2); TOC, total organic carbon; HI, hydrogen index (S2/TOC); OI, oxygen index (S3/TOC)]

Well name	Location	Depth (ft)	Production interval or zone	T_{max} (°C)	S1 (mg/g)	S2 (mg/g)	S3 (mg/g)	PI	TOC (wt.%)	HI	OI
Gulf Oil Co.	8-31S-22E	4,385	Ismay-Des. Ck.	440	0.16	1.85	0.70	0.08	0.62	298	112
No. 1 Hart Point Unit		4,515	Ismay-Des. Ck.	438	1.44	11.58	0.93	0.11	2.34	494	39
		4,635	Ismay-Des. Ck.	439	0.69	6.16	0.74	0.10	1.39	443	53
		7,090	Cane Creek	443	0.22	1.11	0.56	0.17	0.60	185	93
Superior Oil	20-25S-17E	4,310	Ismay-Des. Ck.	438	0.24	0.66	0.18	0.27	0.49	135	37
Bow Knot		5,670	Cane Creek	437	7.65	29.69	1.07	0.20	8.21	362	13
43-20		5,780	Cane Creek	438	2.27	7.86	0.83	0.22	2.75	286	30
		5,830	Cane Creek	436	9.46	40.57	1.13	0.19	10.99	369	10
		5,850	Cane Creek	437	6.62	28.33	0.91	0.19	7.71	367	12
Skelly Oil	26-31S-23E	4,810	Ismay-Des. Ck.	435	0.33	2.03	0.50	0.14	0.76	267	65
No. 1 Church Rock		4,870	Ismay-Des. Ck.	435	0.23	0.92	0.50	0.20	0.58	158	86
		4,930	Ismay-Des. Ck.	440	0.80	3.27	0.66	0.20	1.51	216	43
		5,000	Ismay-Des. Ck.	436	0.11	0.38	0.45	0.23	1.71	22	26
		5,030	Ismay-Des. Ck.	437	0.35	1.19	0.52	0.23	1.47	80	35
		5,060	Ismay-Des. Ck.	436	0.70	2.42	0.97	0.22	1.23	196	78
		5,090	Ismay-Des. Ck.	436	0.75	3.28	0.72	0.19	1.30	252	55
		6,420	Cane Creek	439	10.91	27.40	1.31	0.28	11.06	247	11
		7,940	Cane Creek	436	5.25	13.05	1.48	0.29	4.98	262	29
Superior Oil	14-21S-15E	6,940	Ismay-Des. Ck.	440	0.73	0.40	0.42	0.65	1.07	37	39
No. 14-25		7,000	Ismay-Des. Ck.	444	0.85	0.56	0.25	0.60	1.03	54	24
Grand Fault		7,010	Ismay-Des. Ck.	439	2.05	2.42	0.63	0.46	2.71	89	23
		7,170	Ismay-Des. Ck.	441	0.91	0.41	0.54	0.69	0.94	44	57
		8,960	Cane Creek	462	1.06	0.53	0.45	0.67	1.34	40	34
		9,020	Cane Creek	460	2.19	1.27	0.55	0.63	2.87	44	19
Conoco No. 1	36-27S-13E	5,160	Ismay-Des. Ck.	437	0.29	0.84	0.22	0.26	0.52	162	42
Hanksville		5,360	Ismay-Des. Ck.	430	0.43	0.75	0.64	0.36	0.50	150	128
Standard Oil	32-25S-15E	4,630	Ismay-Des. Ck.	444	0.43	0.82	0.37	0.34	0.80	103	46
No. 1 Moonshine		4,768	Ismay-Des. Ck.	440	2.18	14.21	0.39	0.13	3.37	422	12
		4,858	Ismay-Des. Ck.	432	0.99	7.45	0.52	0.12	2.14	348	24
Pan Am Oil	15-23S-17E	5,100	Ismay-Des. Ck.	440	0.23	0.50	1.16	0.32	0.59	84	196
No. 1 Salt Wash		5,660	Ismay-Des. Ck.	442	1.58	2.19	0.66	0.42	2.26	97	29
		5,790	Ismay-Des. Ck.	443	0.65	0.65	0.57	0.50	1.02	64	56
		5,990	Ismay-Des. Ck.	438	0.84	1.61	2.39	0.34	2.38	67	100
		8,100	Cane Creek	440	4.83	7.94	0.99	0.38	7.41	107	13
		8,150	Cane Creek	443	2.70	4.17	0.77	0.39	4.06	103	19
General	5-24S-15E	4,945	Ismay-Des. Ck.	452	0.04	0.19	0.25	0.17	0.57	33	44
Petroleum		5,130	Ismay-Des. Ck.	425	0.05	0.09	0.15	0.36	0.48	19	31
No. 45-5-G		5,225	Ismay-Des. Ck.	447	0.79	1.45	0.25	0.35	1.26	115	20
		5,298	Ismay-Des. Ck.	444	0.57	1.95	0.63	0.23	1.50	130	42

Table 1. Rock-Eval pyrolysis data, Paradox Formation, Paradox Basin, Utah and Colorado—*Continued*.

Well name	Location	Depth (ft)	Production interval or zone	T_{max} (°C)	S1 (mg/g)	S2 (mg/g)	S3 (mg/g)	PI	TOC (wt.%)	HI	OI
Carbonit	16-39S-21E	5,659	Ismay-Des. Ck.	455	0.67	3.92	0.42	0.15	1.86	210	22
Exploration		5,702	Ismay-Des. Ck.	452	0.69	9.13	0.67	0.07	3.27	279	20
No. 1-16 State		5,704	Ismay-Des. Ck.	444	0.55	4.25	0.64	0.11	1.29	329	49
		5,708	Ismay-Des. Ck.	446	1.17	8.68	0.89	0.16	2.63	330	33
		5,712	Ismay-Des. Ck.	445	1.72	8.97	0.76	0.16	2.38	376	31
McCulloch Oil	4-38N-18W	5,920	Ismay-Des. Ck.	390	0.50	0.73	0.76	0.41	1.12	60	62
Norton Federal		5,925	Ismay-Des. Ck.	368	0.57	0.72	0.77	0.45	1.30	55	59
No. 1-4		5,920	Ismay-Des. Ck.	369	0.51	0.58	0.76	0.47	1.30	44	58
		5,930	Ismay-Des. Ck.	371	0.62	0.66	0.68	0.48	1.47	44	46
		6,042	Ismay-Des. Ck.	484	1.49	7.03	0.60	0.17	10.98	64	5
		6,058	Ismay-Des. Ck.	400	0.16	0.16	0.61	0.50	0.80	20	76
		6,062	Ismay-Des. Ck.	450	0.35	0.52	0.78	0.41	2.71	19	28
		6,066	Ismay-Des. Ck.	454	0.31	0.42	0.49	0.43	2.20	19	22
		6,068	Ismay-Des. Ck.	458	0.50	0.61	0.42	0.45	3.07	19	13
Department of	21-30S-21E	2,758	Ismay-Des. Ck.	450	1.18	12.46	0.83	0.09	2.85	437	29
Energy		2,879	Ismay-Des. Ck.	450	1.17	18.11	0.92	0.06	4.15	436	22
Gibson Dome No. 1		2,951	Ismay-Des. Ck.	435	0.53	2.35	0.62	0.18	1.03	228	60
		3,109	Ismay-Des. Ck.	431	2.91	6.90	0.63	0.29	1.46	472	43
		5,239	Cane Creek	438	4.15	15.27	1.04	0.21	3.96	386	26
Equity Oil	33-21S-21E	11,570	Ismay-Des. Ck.	428	0.44	0.78	4.95	0.36	1.65	47	300
No. 1 Unit		12,500	Ismay-Des. Ck.	335	0.15	0.11	1.38	0.58	0.63	17	219
Belco 1-Floy	11-23S-17E	5,100	Ismay-Des. Ck.	429	0.22	0.78	1.10	0.22	0.56	139	196
Salt Wash		6,000	Ismay-Des. Ck.	415	0.28	0.19	1.12	0.61	0.66	28	169
Texaco	17-23S-17E	5,380	Ismay-Des. Ck.	426	0.46	0.77	1.18	0.38	0.71	108	166
No. 1 Govt.		5,710	Ismay-Des. Ck.	447	1.68	1.79	4.26	0.49	3.0	59	142
Smoot		6,230	Ismay-Des. Ck.	442	1.46	1.57	2.92	0.48	2.28	68	128
		8,230	Cane Creek	445	1.86	3.47	4.52	0.35	4.71	73	95
Tidewater	11-26S-19E	4,602	Ismay-Des. Ck.	429	1.88	12.11	3.02	0.13	4.43	273	68
74-11 Big Flat		4,646	Ismay-Des. Ck.	440	0.12	1.11	1.54	0.10	0.64	173	240
Delhi-Taylor Oil	25-26S-20E	1,847	Ismay-Des. Ck.	439	0.33	2.37	1.35	0.12	1.11	213	121
Cane Creek No. 1		1,881	Ismay-Des. Ck.	443	1.31	11.38	1.82	0.10	3.76	302	48
		2,146	Ismay-Des. Ck.	438	1.11	6.41	3.66	0.15	3.56	180	102
		2,153	Ismay-Des. Ck.	441	1.50	8.08	3.51	0.16	3.93	205	89
		2,159	Ismay-Des. Ck.	440	1.12	6.65	3.35	0.14	3.38	196	99
Delhi-Taylor Oil	15-27S-20E	2,542	Ismay-Des. Ck.	445	6.73	25.66	1.65	0.21	5.97	429	27
Shafer No. 1		2,881	Ismay-Des. Ck.	412	3.5	20.72	1.6	0.14	4.71	439	33
E.B. Larue	15-27S-22E	7,350	Ismay-Des. Ck.	462	0.34	1.02	1.21	0.25	2.32	43	52
Govt. Moab		7,860	Ismay-Des. Ck.	462	0.50	1.71	1.11	0.23	2.80	61	39
Gulf Oil 1 Lockhart	22-28S-20E	2,455	Ismay-Des. Ck.	435	0.19	1.37	0.97	0.12	0.87	183	111
Pure Oil	19-29S-24E	4,200	Ismay-Des. Ck.	439	0.44	1.79	1.31	0.20	0.86	208	152

Table 1. Rock-Eval pyrolysis data, Paradox Formation, Paradox Basin, Utah and Colorado—*Continued*.

Well name	Location	Depth (ft)	Production interval or zone	T_{max} (°C)	S1 (mg/g)	S2 (mg/g)	S3 (mg/g)	PI	TOC (wt.%)	HI	OI
Pure Oil No. 1 NW Lisbon	10-30S-24E	4100	Ismay-Des. Ck.	439	0.34	1.88	1.64	0.15	1.22	154	134
Tennessee Gas	4-31S-12E	4,190	Ismay-Des. Ck.	432	0.31	0.77	1.19	0.29	0.94	81	126
A-2 USA Poison Springs		4,889	Ismay-Des. Ck.	316	0.16	0.32	0.86	0.33	0.33	96	260
Texas Co. No. 2	18-32S-19E	1,610	Ismay-Des. Ck.	430	0.53	3.31	1.22	0.14	1.10	300	110
Cataract Canyon		1,726	Ismay-Des. Ck.	436	0.78	4.12	1.56	0.16	1.29	319	120
Lear Oil 27-11 Jones	27-35S-26E	6,417	Ismay-Des. Ck.	370	0.16	0.73	0.58	0.18	0.81	90	71
Transco 1-32	32-35S-26E	6,435	Ismay-Des. Ck.	464	0.95	2.42	1.30	0.28	3.84	63	33
Pan Am Co.	20-37S-24E	5,803	Ismay-Des. Ck.	448	0.63	1.75	0.98	0.26	1.42	123	69
No. 1		6,120	Ismay-Des. Ck.	446	0.49	5.12	1.58	0.09	2.60	196	60
Dead Man Canyon		7,630	Cane Creek	430	1.31	2.07	1.43	0.39	4.11	50	34
Sinclair Oil	7-38S-18E	2,416	Ismay-Des. Ck.	440	0.10	0.39	0.98	0.21	0.35	111	280
No. 1 Fed. Fehr		2,610	Ismay-Des. Ck.	439	0.21	1.25	1.04	0.14	0.75	166	138
Great Western No.1 Fish Creek	22-38S-20E	2,550	Ismay-Des. Ck.	430	0.15	0.41	0.95	0.27	0.62	66	153
Total Pet. 1-15 Cliffhouse	15-38S-25E	5,633	Ismay-Des. Ck.	416	0.73	1.59	0.67	0.31	1.91	83	35
Mcor Oil and Gas	19-38S-26E	5,721	Ismay-Des. Ck.	455	2.02	4.73	2.32	0.30	3.46	136	67
McCulloch	20-38S-26E	5,518	Ismay-Des. Ck.	448	0.18	0.33	0.74	0.36	0.41	80	180
2 Fed.-20		5,669	Ismay-Des. Ck.	45 1	2.21	6.76	2.56	0.25	3.99	169	64
Shell Oil No. 1	32-39S-23E	5,640	Ismay-Des. Ck.	432	0.10	0.48	0.89	0.17	0.30	160	296
Bluff Unit		5,958	Ismay-Des. Ck.	444	0.73	4.92	2.10	0.13	2.55	192	82
Carter Oil 12-114	8-41S-25E	5,625	Ismay-Des. Ck.	441	0.47	2.12	1.8	0.18	1.24	170	145
Ohio Oil No. 1 Navajo	10-43S-21E	4,915	Ismay-Des. Ck.	441	1.01	3.07	2.11	0.07	4.09	319	51
Celsius 1-5 Unit	20-18W-37N	5,911	Ismay-Des. Ck.	465	1.48	2.85	1.97	0.34	4.44	64	44
Davis Oil No. 1 State line Fee	22-39N-20W	6288	Ismay-Des. Ck.	390	0.47	1.63	0.71	0.32	2.02	81	35

about 0.45 percent R_o to 0.50 percent R_o for high-sulfur kerogen, to 0.60 percent R_o for marine kerogen, to 0.65 percent R_o for terrestrial kerogen. The end of oil generation also occurs over a range of vitrinite reflectance values, but 1.35 percent R_o is commonly accepted as the value at which oil begins to break down into shorter chain hydrocarbons. Dow (1977) stated that oil generation by liptinitic-rich source rocks occurs between 0.50 and 1.35 percent R_o. Wet gas is

Table 2. Vitrinite reflectance data, Paradox Basin, Utah and Colorado.

[Location given as section-township-range. U. Hon. Trail, Upper Honaker Trail; Des. Ck., Desert Creek]

Well name or sample no.	Location	Depth (feet)	Production interval or zone	Vitrinite reflectance (R_o, in percent)
PH91KF59	35-37N-9W	Outcrop	Ismay	1.58
PH91KF6	24-37N-9W	Outcrop	Cane Creek	1.62
PH91KF10	24-37N-9W	Outcrop	Cane Creek	1.52
KF90PB1	18-30S-25E	Outcrop	U. Hon. Trail	0.97
91PCH1HT	?-41S-18E	Outcrop	Ismay-Des. Ck.	0.49
Gibson Dome	21-30S-21E	2,888	Ismay-Des. Ck.	0.73
No. 1		2,890	Ismay-Des. Ck.	0.52
		2,895	Ismay-Des. Ck.	0.70
		5,256	Cane Creek	1.09
Elk Ridge	30-37S-19E	2,812	Ismay-Des. Ck.	0.43
No. 1		2,988	Ismay-Des. Ck.	0.67
General	5-24S-15E	5,443	Ismay-Des. Ck.	1.04
Petroleum		6,180	Cane Creek	1.24
No. 45-5-G		6,681	Cane Creek	1.49
Pan Am	15-23S-17E	5,910	Ismay-Des. Ck.	1.28
No. 1 Salt Wash		5,660	Ismay-Des. Ck.	1.15
		7,620	Cane Creek	1.49
		8,100	Cane Creek	1.85
Standard Oil	32-25S-15E	4,630	Ismay-Des. Ck.	0.88
No. 1 Moonshine		4,768	Ismay-Des. Ck.	0.92
		4,858	Ismay-Des. Ck.	0.93
Superior Oil	20-25S-17E	3,400	Ismay-Des. Ck.	0.59
Bow Knot		4,630	Ismay-Des. Ck.	0.92
43-20		5,580	Cane Creek	1.08
		5,670	Cane Creek	1.07
		5,830	Cane Creek	1.03
Conoco No. 1 So.	36-27S-13E	4,860	Ismay-Des. Ck.	0.85
Hanksville		5,160	Ismay-Des. Ck.	0.90
Superior Oil	14-21S-15E	8,840	Cane Creek	1.72
14-25 Grand		9,080	Cane Creek	1.82
Fault		9,250	Cane Creek	1.72
Skelly Oil No. 1	26-31S-23E	5,000	Ismay-Des. Ck.	0.72
Church Rock		7,940	Cane Creek	0.73
Gulf Oil No. 1	8-31S-22E	4,510	Ismay-Des. Ck.	0.69
Hart Point Unit		7,180	Cane Creek	0.63

generated from mixed lacustrine-marine-terrestrial organic matter and from the thermal cracking of oil between R_o values of 0.80 and 2.0 percent. Thermogenic methane is generated from humic organic matter and from the breakdown of wet gas between R_o values of about 1.0 percent and 3.0 percent. Biogenic gas can be generated at levels of maturity as low as those for peat (0.20 percent R_o).

For this study, T_{max}, PI, and R_o were used in conjunction to define the thermal maturity of the Paradox Formation source rocks. This approach was taken because no single maturity indicator was consistent for all samples. Several factors can influence the results of each of the three maturity indicators used; for a complete explanation and discussion, see Peters (1986) and Nuccio and Barker (1989). T_{max} values vary quite a bit , even for closely spaced samples within a single well (table 1). Production indices are fairly consistent within a single well and throughout the basin. Vitrinite reflectance values correlate well with production indices and serve to corroborate them (fig. 7). The following table illustrates the correlation between T_{max}, production index (PI), and vitrinite reflectance (R_o) and the levels of thermal maturity and petroleum generation used in this study:

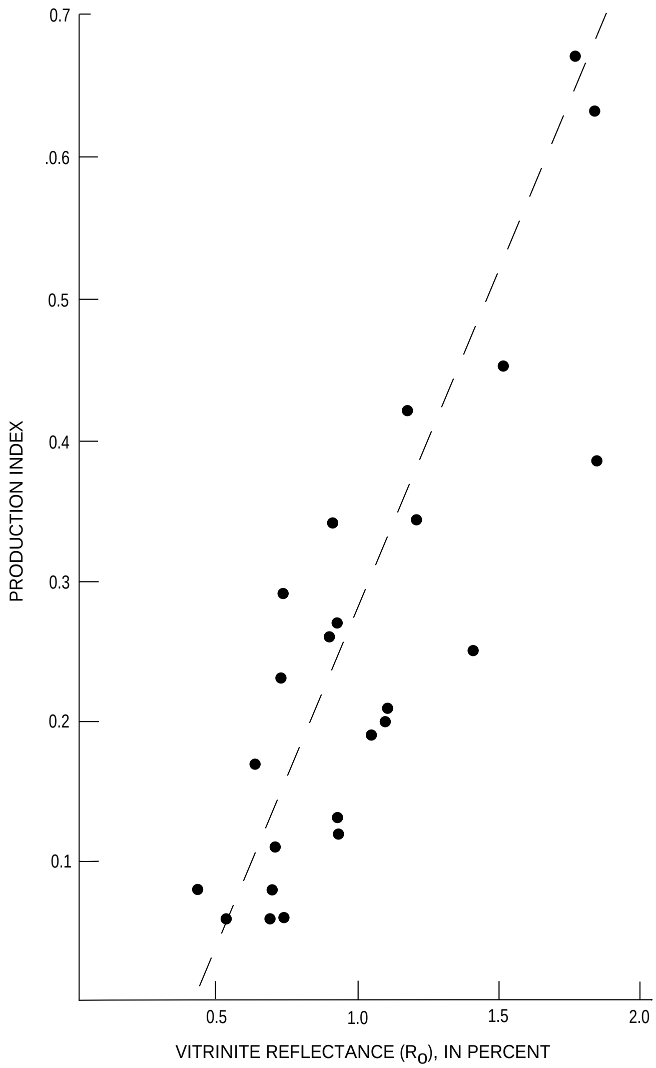


Figure 7. Production index (PI) versus vitrinite reflectance (R_o) for samples from the Ismay–Desert Creek interval and Cane Creek cycle of the Paradox Formation. Correlation is a best-fit line.

	T_{max} (°C)	PI	R_o (percent)
Immature for oil	<435	<0.08	<0.60
Mature for oil	435–460	0.80–0.50	0.60–1.35
Overmature for oil-dry gas zone	>460	>0.50	>1.35

Burial curves (sometimes called geohistory curves) were constructed for six distinctively different areas using a variety of information. Cambrian through Jurassic stratigraphy was reconstructed using the drill-hole database discussed previously, and Cretaceous and Tertiary stratigraphy was reconstructed by extrapolation from nearby areas where these rocks crop out. Numerical ages for the major periods were adapted from Harland and others (1990). Due to the uncertainties associated with determining amounts of erosion, unconformities between formations were treated as hiatuses with no erosion. Table 3 lists the thicknesses and ages used to reconstruct the burial histories of the six areas.

Present-day heat-flow values for the Paradox Basin range from 43 to 105 mWm^{-2} (Bodell and Chapman, 1982; Sass and others, 1983). Heat-flow values are lower in the interior of the Colorado Plateau and are higher around the periphery. The Paradox Basin is mostly within the interior of the Colorado Plateau, and it is likely that heat flow in the basin has been stable throughout its history (Hite and others, 1984). It is possible that the Paradox Basin may be at maximum heat-flow today (Bodell and Chapman, 1982; R.J. Hite, oral commun., 1993). The measured thermal maturity data (T_{max}, PI, and R_o) discussed previously were used to calibrate the thermal history models. Assuming that our burial curves are representative of the six different areas, the heat flow was adjusted either upward or downward until the modeled thermal maturity trends matched the measured data.

Once the modeled thermal maturity data were brought into agreement with the measured thermal maturity, hydrocarbon-generation kinetic models were constructed to determine the petroleum-generation history of the Paradox Formation throughout the basin. The computer program BasinMod (Platte River Associates, 1992) was used for the thermal and kinetic modeling. Kinetic modeling is useful in estimating the time at which the Paradox Formation was in the oil window. It is the best method for predicting petroleum-generation history because it is based on the kinetic reactions of organic matter during burial and thermal maturation rather than on just temperature. In the model, all reactions are treated as first-order reactions; that is, the rate is proportional to the amount of reactant. The Arrhenius equation is used to describe the temperature dependence of the rate constant. The result of the modeling relates the amounts of oil and gas to time and temperature for a particular kerogen or mix of kerogens. For a complete explanation of kinetic modeling, see discussions in Tissot and Espitalie (1975), Ungerer (1983), Yukler and Kokesh (1984), Sweeney and others (1987), and Tissot and others (1987).

KEROGEN TYPES AND RELATED HYDROCARBONS

Three general types of kerogen have the potential, under optimum conditions, to generate hydrocarbons: type I, alginite (sapropelic or lipid-rich); type II, exinite (phytoplankton, zooplankton, and other microorganisms); and type III, vitrinite and huminite (terrestrial plant debris). There is no absolute point at which hydrocarbon generation starts, and it probably begins over a range of maturity values (and temperatures) depending on the specific type of organic matter. Several models have been developed that relate the generation of hydrocarbons to types of kerogen and thermal maturity (Tissot and others, 1974; Dow, 1977; Waples, 1980, 1985). It

Table 3. Data used to construct burial curves for six areas studied in the Paradox Basin, Utah and Colorado.

[ss, sandstone; sh, shale; carb, carbonate; lime, limestone; mud, mudstone; silt, siltstone; evap, evaporite; Penn, Pennsylvanian; L., Lower; M., Middle; U., Upper]

System/series, unit, or event	Age range (Ma)	Thickness (feet)	Thickness (meters)	Generalized lithology
Monument upwarp area				
Uplift and erosion	25–0	–10,550	–3,216	
Tertiary	66–25	1,000	305	75% ss, 25% sh
Unconformity	74–66	0	0	
Cretaceous	97–74	5,800	1,768	25% ss, 75% sh
Unconformity	146–97	0	0	
U. and M. Jurassic	174–146	1,400	427	60% ss, 40% mud
Unconformity	178–174	0	0	
L. Jurassic	205–178	900	275	60% ss, 40% mud
Unconformity	208–205	0	0	
U. Triassic	220–208	900	275	50% ss, 50% sh
Unconformity	225–220	0	0	
L. Triassic	235–225	300	92	50% ss, 50% sh
Unconformity	255–235	0	0	
Permian	290–255	1,750	533	70% ss, 30% silt
Pennsylvanian	327–290	2,285	696	
Honaker Trail Fm	300–290	900	275	15% sh, 85% carb
Ismay-Desert Ck	303–300	360	110	15% sh, 85% carb
Middle Penn	307–303	700	213	15% sh, 80% carb, 5% evap
Lower Penn	327–307	325	100	20% sh, 80% carb
Unconformity	345–327	0	0	
Mississippian	358–345	450	137	100% limestone
Unconformity	363–358	0	0	
Devonian	409–363	650	198	25% ss, 15% sh, 60% carb
Unconformity	510–409	0	0	
Cambrian	570–510	500	152	50% ss, 40% sh, 10% carb
Confluence of the Green and Colorado Rivers				
Uplift and erosion	25–0	–10,350	–3,155	
Tertiary	66–25	1,000	305	75% ss, 25% sh
Unconformity	74–66	0	0	
Cretaceous	97–74	5,800	1,768	25% ss, 75% sh
Unconformity	146–97	0	0	
U. and M. Jurassic	174–146	1,150	350	60% ss, 40% mud
Unconformity	178–174	0	0	
L. Jurassic	205–178	1,150	350	60% ss, 40% mud
Unconformity	208–205	0	0	
U. Triassic	220–208	500	152	50% ss, 50% sh
Unconformity	225–220	0	0	
L. Triassic	235–225	450	137	50% ss, 50% sh
Unconformity	255–235	0	0	
Permian	290–255	1,500	457	65% ss, 20% silt, 15% carb
Pennsylvanian	327–290	3,625	1,105	
Honaker Trail	300–290	1,100	335	15% sh, 85% carb
Ismay-Desert Ck	303–300	400	122	15% sh, 75% carb, 10% evap
Middle Penn	307–303	1,700	518	20% sh, 10% carb, 70% evap
Lower Penn	327–307	425	130	20% sh, 30% carb, 50% evap
Unconformity	345–327	0	0	
Mississippian	358–345	500	152	100% limestone
Unconformity	363–358	0	0	
Devonian	409–363	375	114	25% ss, 15% sh, 60% carb
Unconformity	510–409	0	0	
Cambrian	570–510	1,050	320	50% ss, 40% sh, 10% carb

Table 3. Data used to construct burial curves for six areas studied in the Paradox Basin, Utah and Colorado—*Continued*.

System/series, unit, or event	Age range (Ma)	Thickness (feet)	Thickness (meters)	Generalized lithology
Green River, Utah				
Uplift and erosion	37–0	–8,050	–2,454	
Tertiary	66–37	2,000	610	25% ss, 75% sh
Unconformity	74–66	0	0	
Cretaceous	97–74	6,000	1,829	25% ss, 75% sh
Unconformity	146–97	0	0	
U. and M. Jurassic	174–146	1,450	442	55% ss, 45% mud
Unconformity	178–174	0	0	
L. Jurassic	205–178	1,000	305	55% ss, 45% mud
Unconformity	208–205	0	0	
U. Triassic	220–208	400	122	50% ss, 50% sh
Unconformity	225–220	0	0	
L. Triassic	235–225	800	244	50% ss, 50% sh
Unconformity	255–235	0	0	
Permian	290–255	1,250	381	65% ss, 20% silt, 15% carb
Pennsylvanian	327–290	2,460	750	
Honaker Trail	300–290	750	230	15% sh, 85% carb
Ismay-Desert Ck	303–300	360	110	15% sh, 45% carb, 40% evap
Middle Penn	307–303	1,000	305	20% sh, 10% carb, 70% evap
Lower Penn	327–307	350	107	20% sh, 30% carb, 50% evap
Unconformity	345–327	0	0	
Mississippian	358–345	650	198	100% limestone
Unconformity	363–358	0	0	
Devonian	409–363	350	107	15% sh, 85% carb
Unconformity	510–409	0	0	
Cambrian	570–510	1,250	381	10% ss, 45% sh, 45% carb
Moab, Utah				
Uplift and erosion	37–0	–11,575	–3,528	
Tertiary	66–37	2,000	610	25% ss, 75% sh
Unconformity	74–66	0	0	
Cretaceous	97–74	5,900	1,798	25% ss, 75% sh
Unconformity	146–97	0	0	
U. and M. Jurassic	174–146	1,125	343	55% ss, 45% mud
Unconformity	178–174	0	0	
L. Jurassic	205–178	1,250	381	55% ss, 45% mud
Unconformity	208–205	0	0	
U. Triassic	220–208	400	122	50% ss, 50% sh
Unconformity	225–220	0	0	
L. Triassic	235–225	400	122	50% ss, 50% sh
Unconformity	255–235	0	0	
Permian	290–255	4,500	1,372	80% ss, 20% sh
Pennsylvanian	327–290	6,310	1,923	
Honaker Trail	300–290	1,950	595	20% ss, 15% sh, 65% carb
Ismay-Desert Ck	303–300	860	262	20% sh, 20% carb, 60% evap
Middle Penn	307–303	2,400	732	15% sh, 10% carb, 75% evap
Lower Penn	327–307	1,100	335	20% sh, 20% carb, 60% evap
Unconformity	345–327	0	0	
Mississippian	358–345	400	122	100% limestone
Unconformity	363–358	0	0	
Devonian	409–363	325	100	10% ss, 10% sh, 80% carb
Unconformity	510–409	0	0	15% sh, 85% carb
Cambrian	570–510	900	275	35% ss, 30% sh, 35% carb

Table 3. Data used to construct burial curves for six areas studied in the Paradox Basin, Utah and Colorado—*Continued*.

System/series, unit, or event	Age range (Ma)	Thickness (feet)	Thickness (meters)	Generalized lithology
Lisbon Valley, Utah, area				
Uplift and erosion	25–0	–13,350	–4,069	
Tertiary	66–25	1,000	305	50% ss, 50% sh
Unconformity	74–66	0	0	
Cretaceous	97–74	6,000	1,829	25% ss, 75% sh
Unconformity	146–97	0	0	
U. and M. Jurassic	174–146	1,050	320	65% ss, 35% mud
Unconformity	178–174	0	0	
L. Jurassic	205–178	1,000	305	65% ss, 35% mud
Unconformity	208–205	0	0	
U. Triassic	220–208	550	168	50% ss, 50% sh
Unconformity	225–220	0	0	
L. Triassic	235–225	0	0	50% ss, 50% sh
Unconformity	255–235	0	0	
Permian	290–255	3,750	1,143	80% ss, 20% sh
Pennsylvanian	327–290	8,200	2,500	
Honaker Trail	300–290	1,900	580	10% ss, 15% sh, 75% carb
Ismay-Desert Ck.	303–300	500	152	20% sh, 20% carb, 60% evap
Middle Penn	307–303	4,900	1,494	15% sh, 5% carb, 80% evap
Lower Penn	327–307	900	275	20% sh, 20% carb, 60% evap
Unconformity	345–327	0	0	
Mississippian	358–345	400	122	100% limestone
Unconformity	363–358	0	0	
Devonian	409–363	300	91	10% ss, 10% sh, 80% carb
Unconformity	510–409	0	0	
Cambrian	570–510	550	168	50% ss, 25% sh, 25% carb
Hermosa, Colo.				
Uplift and erosion	25–0	–12,550	–3,825	
Tertiary	66–25	2,500	762	60% ss, 40% sh
Unconformity	74–66	0	0	
Cretaceous	97–74	6,250	1,905	25% ss, 75% sh
Unconformity	146–97	0	0	
U. and M. Jurassic	174–146	900	274	65% ss, 35% mud
Unconformity	178–174	0	0	
L. Jurassic	205–178	0	0	65% ss, 35% mud
Unconformity	208–205	0	0	
U. Triassic	220–208	600	183	50% ss, 50% sh
Unconformity	225–220	0	0	
L. Triassic	235–225	0	0	50% ss, 50% sh
Unconformity	255–235	0	0	
Permian	290–255	2,500	762	90% ss, 10% mud
Pennsylvanian	327–290	2,770	844	
Honaker Trail	300–290	730	223	70% ss, 25% silt, 5% lime
Ismay-Desert Ck.	303–300	300	91	34% ss, 33% silt, 33% lime
Middle Penn	307–303	1,320	402	60% ss, 20% silt, 20% carb
Lower Penn	327–307	420	128	50% ss, 10% sh, 40% lime
Unconformity	345–327	0	0	
Mississippian	358–345	150	46	100% limestone
Unconformity	363–358	0	0	
Devonian	409–363	175	53	25% ss, 20% sh, 55% carb
Unconformity	510–409	0	0	
Cambrian	570–510	50	15	100% ss

should be noted that there is another type of kerogen, type IV, which is composed of inert organic matter (oxidized and biologically altered organic matter, charcoal, and recycled organic matter); it has low hydrogen content and virtually no hydrocarbon-generation potential.

Type I kerogen is hydrogen rich, is primarily in marine and lacustrine rocks, and generates mainly oil during catagenesis. The vitrinite reflectance value for the onset of oil generation from type I organic matter varies depending on the model. Dow (1977) used 0.50 percent R_o as the onset of oil generation for type I kerogen, whereas Anders and Gerrild (1984) and Tissot and Welte (1984) used 0.70 percent R_o.

Type II kerogen is mainly in marine rocks but can be present in lacustrine rocks, and it generates oil and gas during catagenesis. Waples (1985) stated that oil generation from type II kerogen begins over a range of R_o values of about 0.45–0.50 percent for high-sulfur kerogen to 0.60 percent for "typical" type II kerogen.

Huminite and vitrinite, or type III kerogen, is oxygen rich and hydrogen poor; is mainly in terrestrial, marginal-lacustrine, or marginal-marine rocks; and generates mostly gas (methane) during catagenesis. For type III kerogen, vitrinite reflectance is the best and most widely used measure of thermal maturity. Two important reflectance thresholds are used to define regions of gas generation from type III kerogen: these are 0.75 percent and 1.10 percent. An R_o of about 0.75 percent represents the maturity required for the onset of significant gas generation (Juntgen and Karweil, 1966; Juntgen and Klein, 1975). Gas accumulations in rocks having an R_o of less than 0.75 percent contain either early biogenic gas or gas migrated from more mature source rocks. An R_o of 1.10 percent represents the level of maximum gas expulsion from type III kerogen (Meissner, 1984). The upper limit of maturity for gas preservation is unknown but could be as high as 3.5 percent R_o (Dow, 1977) or 4.0 percent R_o (Waples, 1980).

SOURCE ROCK POTENTIAL OF THE ISMAY–DESERT CREEK INTERVAL AND CANE CREEK CYCLE

As mentioned previously, total organic carbon (TOC) content is a useful parameter for evaluating the amount of organic material and the petroleum-generation potential of a source rock. For this study, we assumed that if shale within the Ismay–Desert Creek interval and the Cane Creek cycle has TOC values ≥0.50 percent, it is a good source rock. Table 1 shows that only 6 (all in the Ismay–Desert Creek interval) of the 107 samples had total organic carbon contents of less than 0.50 percent. The most striking and important feature of these shales is the high total organic carbon content—as high as 11.0 percent. These high values are somewhat biased and probably do not represent the intervals as a whole; when collecting samples, dark-gray to black shale was generally chosen. These values do demonstrate, however, that there are very organically rich zones in both the Ismay–Desert Creek interval and the Cane Creek cycle and that both have excellent petroleum-generation potential.

Another parameter used to evaluate the hydrocarbon-generating capacity of a source rock is the genetic potential or S1 + S2. Tissot and Welte (1984) established a genetic potential classification, as follows:

(S1 + S2) (mg/g)	Source rock characterization
<2.0	Poor source rock or non-source rock.
2.0–6.0	Moderate source rock.
>6.0	Good to excellent source rock.

Using this classification, 62 percent of all samples have (S1 + S2) >2.0 mg/g and are considered to be moderate to excellent source rocks (table 1).

As mentioned in the previous section, organic matter type determines the quality and kind of hydrocarbons generated. The most widely used parameter for defining the type of organic matter contained in a source rock is the modified

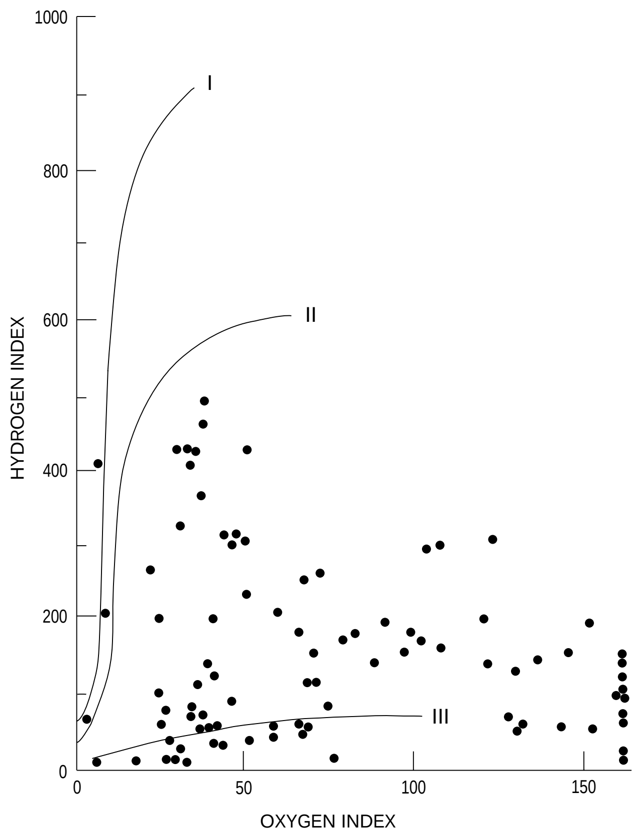


Figure 8. Modified van Krevelen diagram for samples from the Ismay–Desert Creek interval. Type I kerogen generates mainly oil; type II kerogen generates oil and gas; and type III kerogen generates mainly gas.

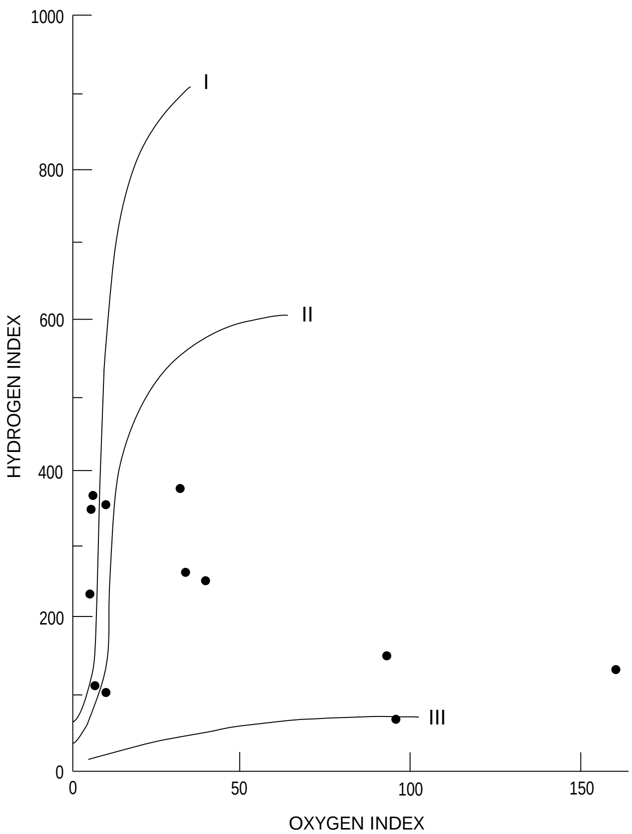


Figure 9. Modified van Krevelen diagram for samples from the Cane Creek cycle. Type I kerogen generates mainly oil; type II kerogen generates oil and gas; and type III kerogen generates mainly gas.

van Krevelen diagram (van Krevelen, 1961; Tissot and Welte, 1984). This diagram plots hydrogen index versus oxygen index as determined from Rock-Eval analysis and illustrates the type of organic matter and its relative position on the maturation evolutionary path. Figures 8 and 9 are modified van Krevelen diagrams for the Ismay–Desert Creek interval and the Cane Creek cycle, respectively.

The modified van Krevelen diagram of the Ismay–Desert Creek interval (fig. 8) shows mainly types II and III organic matter, sources for both oil and gas. We believe that the organic matter is of both marine and terrestrial origin, with a transition zone between the two (types II and III). The transition zone may consist of either (1) a mixture of types II and III kerogen, (2) an area having type II kerogen and a relatively low hydrogen index, or (3) an area having type III kerogen and a relatively higher hydrogen index. A few samples plot near the type I line and are likely to be good source rocks for oil. Samples nearer the eastern part of the basin may be more terrestrial in origin and are likely to be good source rocks for mainly gas. For example, Ismay–Desert Creek samples from the Norton Federal 1-4 well in sec. 4, T. 38 N., R. 18 W. (table 1) plot near the type III line. Similarly, a carbonaceous shale from the Ismay interval (PH91KF59), collected from outcrop near Hermosa, Colo., on the easternmost edge of the basin, comprised organic matter having a terrestrial affinity.

The wide distribution of samples on the diagrams not only is due to differences in organic matter type and source but also to the degree of thermal maturation. In general, plotted samples migrate toward the origin of the diagram (HI=0, OI=0) with increasing thermal maturity. Caution should be taken when interpreting the origin and source of organic matter in samples that have a high level of thermal maturation. For example, a rock that originally had an HI=400 and an OI=75 (type II kerogen of marine origin) will decrease in hydrogen and oxygen indices with increasing thermal maturation (migrate toward the origin of the diagram) and will ultimately plot as a type III kerogen. The wide range of plotted samples in figure 8 is indicative of variations in kerogen type as well as differences in the thermal history of the basin.

The modified van Krevelen diagram of the Cane Creek cycle (fig. 9) illustrates that this unit contains types I, II, and III kerogen, sources for both oil and gas. Samples from the Cane Creek cycle are more mature than those from the Ismay–Desert Creek interval and generally have lower hydrogen indices. This is not to say that, before maturation, the Cane Creek was not as good a source rock as the Ismay–Desert Creek, but, because the Cane Creek is mature everywhere in the basin, several of the samples probably plot closer to the origin of the diagram.

As with the Ismay–Desert Creek interval, organic matter in the lower part of the Paradox Formation near the eastern side of the basin has a more terrestrial origin. For example, humic coals (samples PH91KF6 and PH91KF10) were collected just below the Cane Creek cycle on the extreme eastern side of the basin near Hermosa, Colo. Some Cane Creek cycle samples in the central part of the basin also plot near the type III line. For example, a Cane Creek sample from the Texaco No. 1 Gov't. Smoot well in sec. 17, T. 23 S., R. 17 E. plots on the type III line. Caution should be taken, however, in interpreting kerogen type because the maturity of this sample is fairly high in that it has a PI of 0.35 and a T_{max} of 445°C.

THERMAL MATURITY TRENDS

Thermal maturity maps for the Paradox Basin illustrating the highly variable maturation trends for two horizons, the Ismay–Desert Creek interval in the upper part of the Paradox Formation and the Cane Creek cycle of the Alkali Gulch interval near the bottom of the Paradox Formation, were constructed using production indices (PI) from Rock-Eval pyrolysis and some vitrinite reflectance data. Production index was chosen because it is more consistent in the Paradox Formation than either T_{max} or vitrinite reflectance and represents, fairly well, the maturity within the intervals for a given well, as well as for the entire basin. Data points

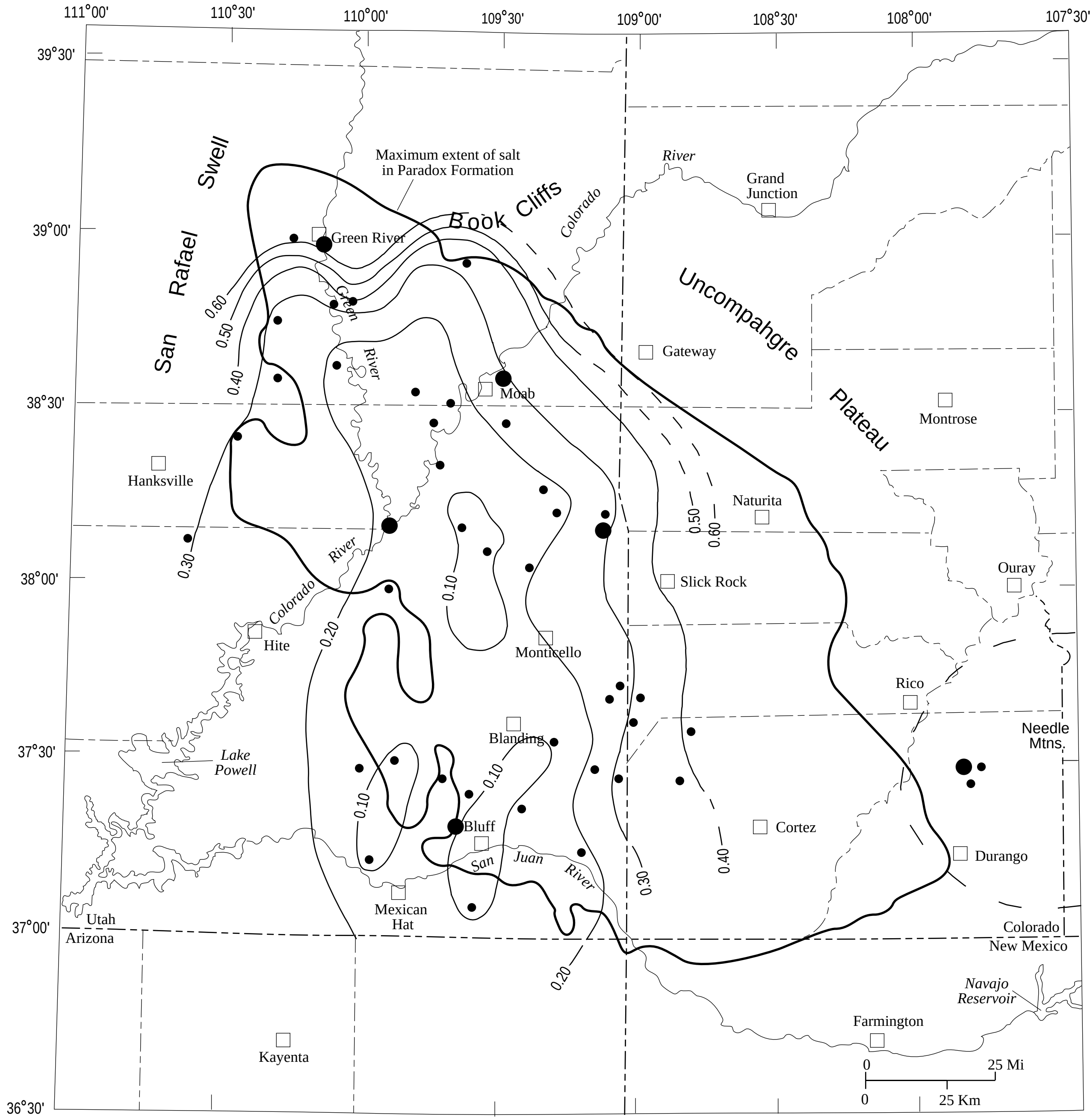


Figure 10. Thermal maturity map of the Paradox Basin at the Ismay–Desert Creek interval. Contours are production indices, interval = 0.10. Large dots are locations of the six areas where burial, thermal, and petroleum-generation histories were reconstructed; small dots are production-index control points.

on the maps of the Ismay–Desert Creek interval (fig.10) and the Cane Creek cycle (fig. 11) are listed and correspond to table 1. Vitrinite reflectance data (table 2) supplement the large production index data set and serve as a check (analytical comparison) on the thermal maturity. In almost every case, vitrinite reflectance corroborates the thermal maturity derived from production index data.

ISMAY–DESERT CREEK INTERVAL

The thermal maturity map of the Ismay–Desert Creek interval (fig. 10) shows a general trend of increasing maturity from southwest to northeast. This trend corresponds with the thickening of Pennsylvanian and Permian units (fig. 5). In Pennsylvanian and Permian time, the eastern part of the basin

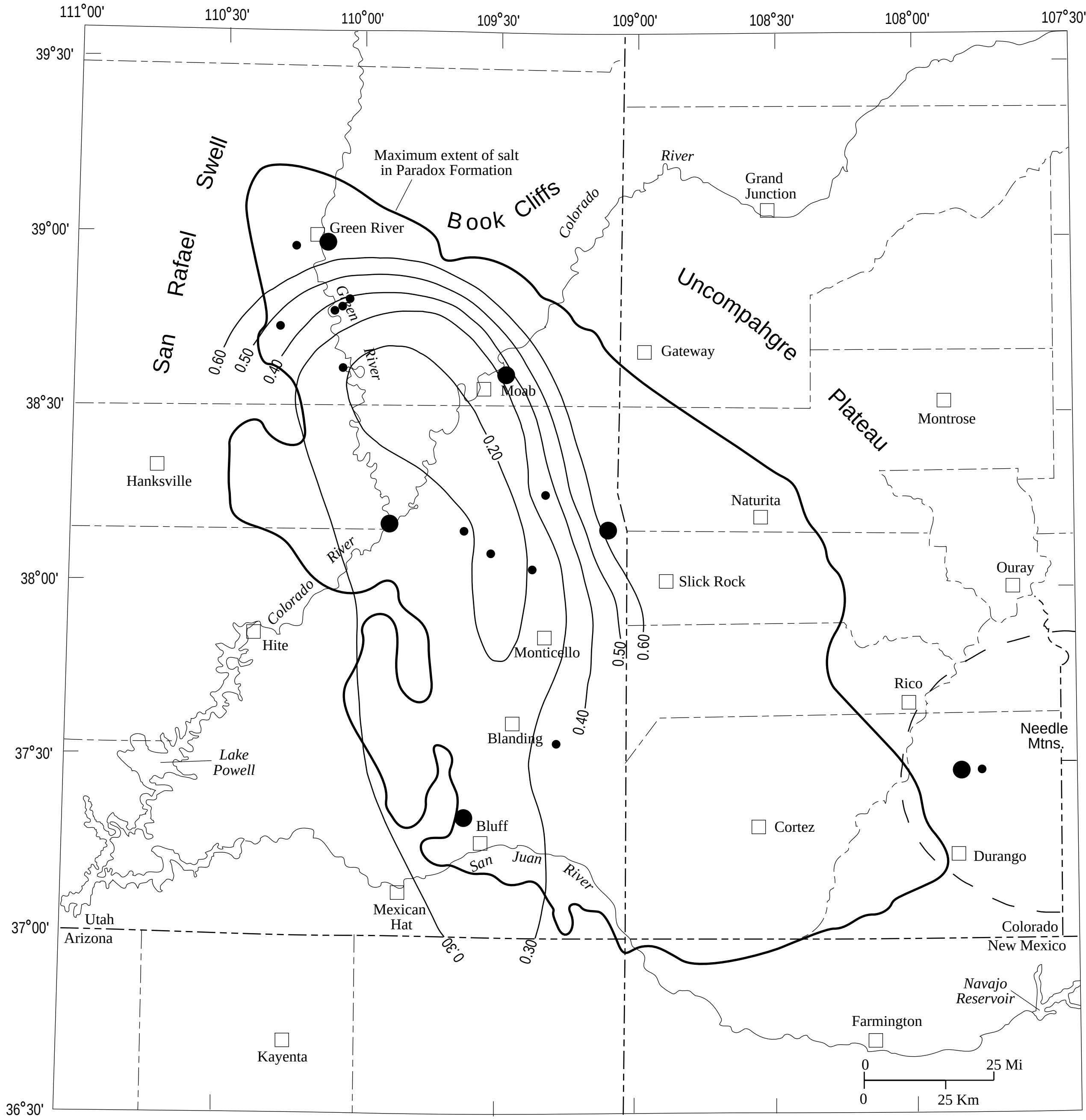


Figure 11. Thermal maturity map of the Paradox Basin at the Cane Creek cycle. Contours are production indices, interval = 0.10. Large dots are locations of the six areas where burial, thermal, and petroleum-generation histories were reconstructed; small dots are production-index control points.

subsided rapidly, and a thick sedimentary sequence accumulated. As a direct result of the greater depth of burial in the eastern part of the basin, the thermal maturity is greater there. In the northernmost part of the basin, the thermal maturity of the Ismay–Desert Creek is also very high. In this area, the high thermal maturity is most likely the result of greater depth of burial during Tertiary time when a thick sedimentary package was deposited there.

Areas of high thermal maturity may be present throughout the basin but are not represented by the generalized production index contours. High heat flow associated with Tertiary igneous events such as the La Sal, Henry, Abajo, and San Juan Mountains affected immediately adjacent areas; however, these heat sources were fairly localized and are not noticeable at a basinwide scale or within the resolution of the contours. An area of high thermal maturity

(R_o = 1.58 percent) is in the southeastern part of the study area near Hermosa, Colo. (table 2). This part of the basin has been penetrated by several Tertiary intrusive stocks, dikes, and sills and experienced a higher heat flow in the Tertiary than the rest of the basin.

Localized low-maturity areas, such as salt anticlines, also likely are present, especially within the area of high maturity in the northeastern part of the basin. These salt anticlines are thought to have been actively growing since Late Pennsylvanian time—in these positive-relief areas, deposition of Pennsylvanian and Permian sediments, as well as younger Mesozoic sediments, may have been significantly less than in the adjacent synclines. Differences in the burial histories between the anticlines and synclines are significant but localized and are not obvious when compared to the regional thermal maturity trends represented by basin-scale maps. A much smaller scale study is needed to detail the maturity differences for the salt anticline areas.

The thermal maturity map of the Ismay–Desert Creek interval (fig. 10) reveals three areas of PI ≤0.10 that represent the most immature parts of the basin. As previously discussed, a production index of 0.08 is the minimum threshold for significant oil generation, and a few such low values are present in the immature areas; however, based on the fact that oil is produced in these “immature” areas, good-quality source rocks in the areas with PI ≤0.10 may have the sufficient thermal maturity to have generated at least some petroleum.

Production indices between 0.08 and 0.50 represent thermal maturity levels sufficient for significant petroleum generation. Figure 10 illustrates that the Ismay–Desert Creek interval is within these levels of thermal maturity in most of the basin. Except for the overmature northern and easternmost parts of the basin, source rocks in the Ismay–Desert Creek interval in most of the basin could be considered to have the potential for generation, accumulation, and possible migration of petroleum.

In the areas where production indices exceed 0.50, one would expect maturities to be too high for the preservation of oil. Unless there was a later, postmaturation migration of oil from a less mature part of the basin, reservoirs in the PI >0.50 areas should not contain oil. In these areas of high maturity,

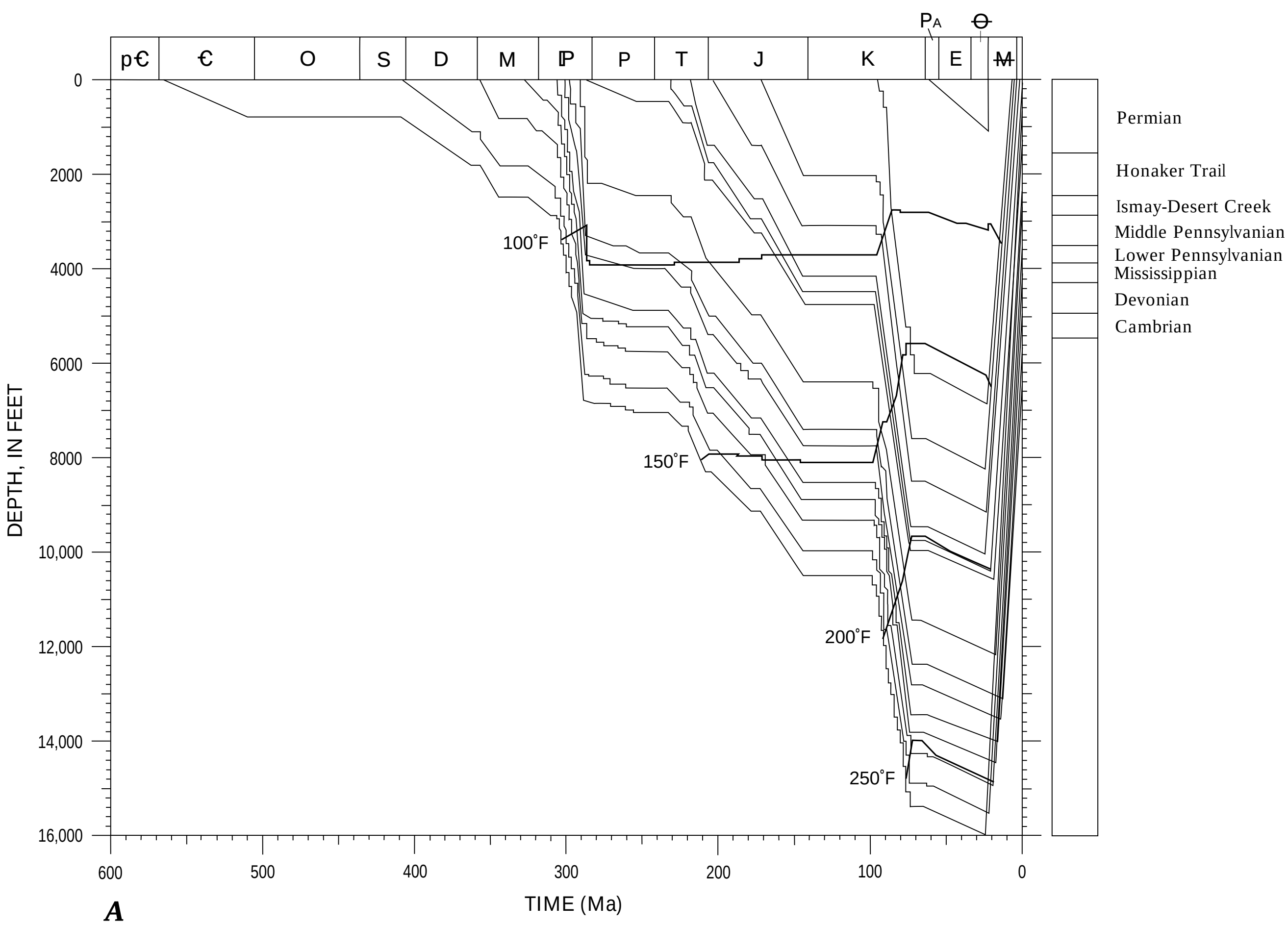


Figure 12. Burial, thermal, and petroleum-generation model of the area near the Monument upwarp (see figs. 1 and 2). *A*, Cambrian through present. *B*, Expanded time scale illustrating 100 Ma to present.

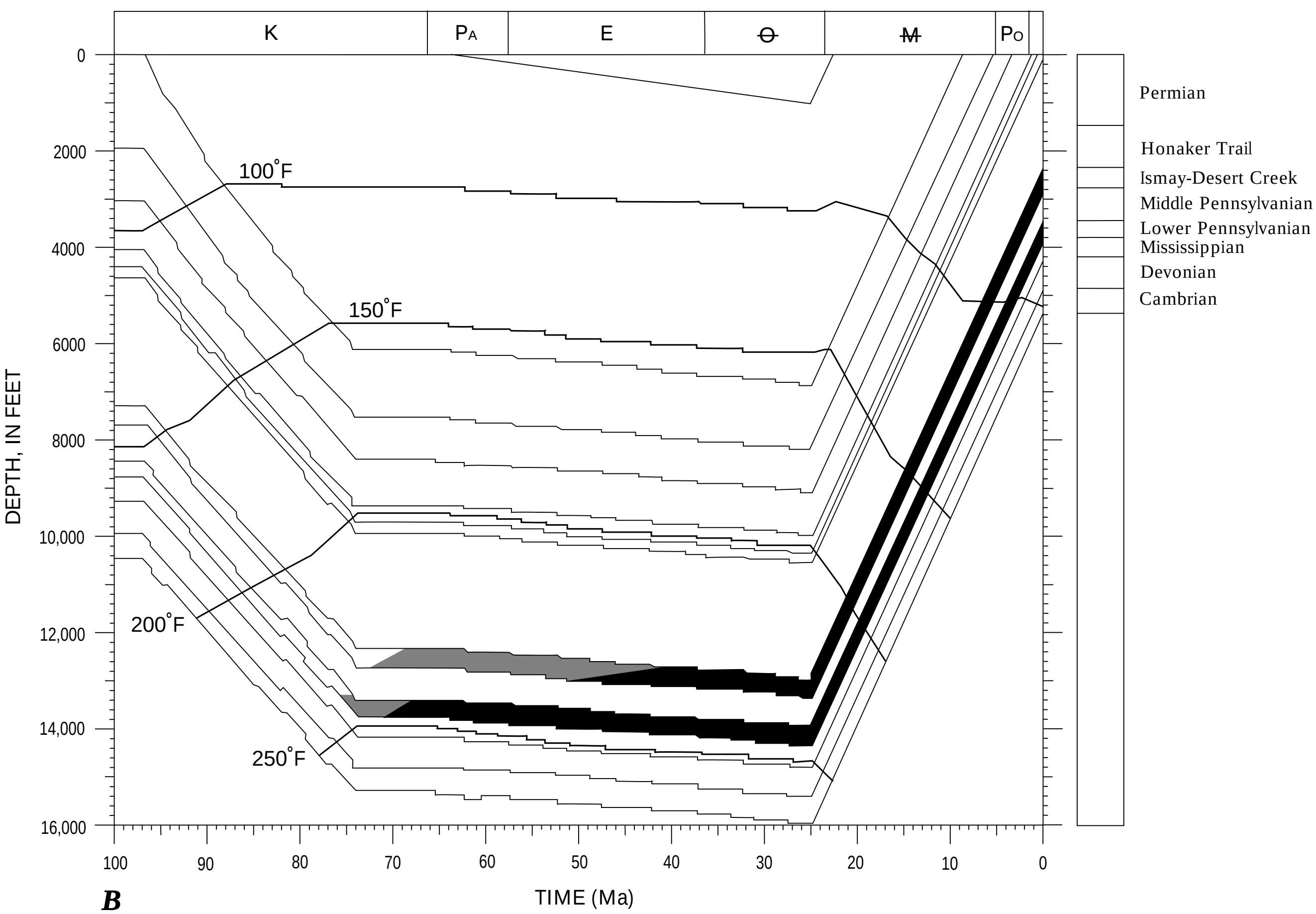
it is very likely, however, that thermogenic gas generated from kerogen in the rocks, as well as gas and condensate generated from the cracking of oil, may be present. The distribution of petroleum and its relationship to thermal maturity will be discussed in a later section.

CANE CREEK CYCLE

Thermal maturity trends at the Cane Creek cycle (fig. 11) generally follow the structural configuration of the basin and are similar to maturity trends of the Ismay–Desert Creek interval. The maturity of the Cane Creek generally increases from southwest to northeast, and the Cane Creek is the least mature in the west-central part of the basin. The overall level of maturity, however, is higher at the Cane Creek cycle than at the Ismay–Desert Creek interval and is directly related to the thickness of the Pennsylvanian strata overlying the Cane Creek that did not influence the Ismay–Desert Creek interval. Another significant difference between the Cane Creek cycle and the Ismay–Desert Creek interval is that the production index contours are much closer together at the Cane Creek horizon. This also can be explained by the additional thickness of sedimentary rocks overlying the Cane Creek cycle in the rapidly subsiding deeper part of the basin. As a consequence of the greater depth of burial for the Cane Creek cycle, much more of the basin is overmature (>0.50 PI) at this interval (compare figs. 10 and 11). For an explorationist, the target area for oil is significantly smaller at the Cane Creek cycle than at the Ismay–Desert Creek interval.

As with the thermal maturity of the Ismay–Desert Creek interval, thermal maturity in the northernmost part of the basin is very high. This high maturity is a result of thick sedimentation and deep burial during Tertiary time in that part of the basin.

The least mature area at the Cane Creek cycle is in the west-central part of the basin and is represented by the 0.20-PI contour. This production index is much higher than that of the least mature areas at the Ismay–Desert Creek interval, and there are no immature areas at the Cane Creek cycle. The area in which potential source rocks would be mature for oil generation ranges from the 0.20-PI contour to the 0.50-PI contour, and as mentioned earlier, is a much smaller area than at the Ismay–Desert Creek interval. In the areas ≥0.50 PI, the potential for condensate, gas from



B

EXPLANATION

Early generation of hydrocarbons 10% to 25%

Main phase, generation of hydrocarbons 25% to 65%

thermally cracked oil, and thermogenic gas from kerogen in the rock is good.

An area of high thermal maturity, near Hermosa, Colo., similar to that described previously for the Ismay–Desert Creek interval, is evidenced in the Cane Creek cycle by two samples having vitrinite reflectance values of 1.62 and 1.52 percent (table 2). As previously discussed, this part of the basin contains several igneous intrusions and experienced a higher heat flow during Tertiary time. It is hard to determine the pre-Tertiary thermal and petroleum-generation history of Paradox Formation source rocks within this area of high maturity because the Tertiary heating has masked all previous events. It is likely that oil once generated in the area has been destroyed; however, the high maturity should not discount the potential for gas generation and accumulation in this area.

BURIAL, THERMAL, AND PETROLEUM-GENERATION MODELS

The following models illustrate the burial and thermal histories for six areas in the Paradox Basin (shown by large dots on figs. 1, 10, and 11) for the time period of Cambrian through present. Most of the discussion focuses on petroleum generation from the Ismay–Desert Creek interval and the Cane Creek cycle of the Paradox Formation. Two burial, thermal, and petroleum-generation curves are shown for each model: one illustrating Cambrian through present and a second illustrating the last 100 or 200 m.y. The detail curve is necessary to identify important petroleum-generation events, as well as the time period of rapid uplift and erosion between 37 or 25 Ma to present.

MONUMENT UPWARP

The area encompassing the Monument upwarp (figs. 1, 2) is in the least deeply buried, least mature part of the Paradox Basin. The burial history for Cambrian through present is illustrated by figure 12*A*. During late Paleozoic time, this area was in the stable to slowly subsiding western shelf region of the basin and is characterized by a relatively thin Pennsylvanian and Permian stratigraphic section (fig. 5, table 3). During Triassic and Jurassic time, only a relatively moderate to thin stratigraphic section was deposited (fig. 6,

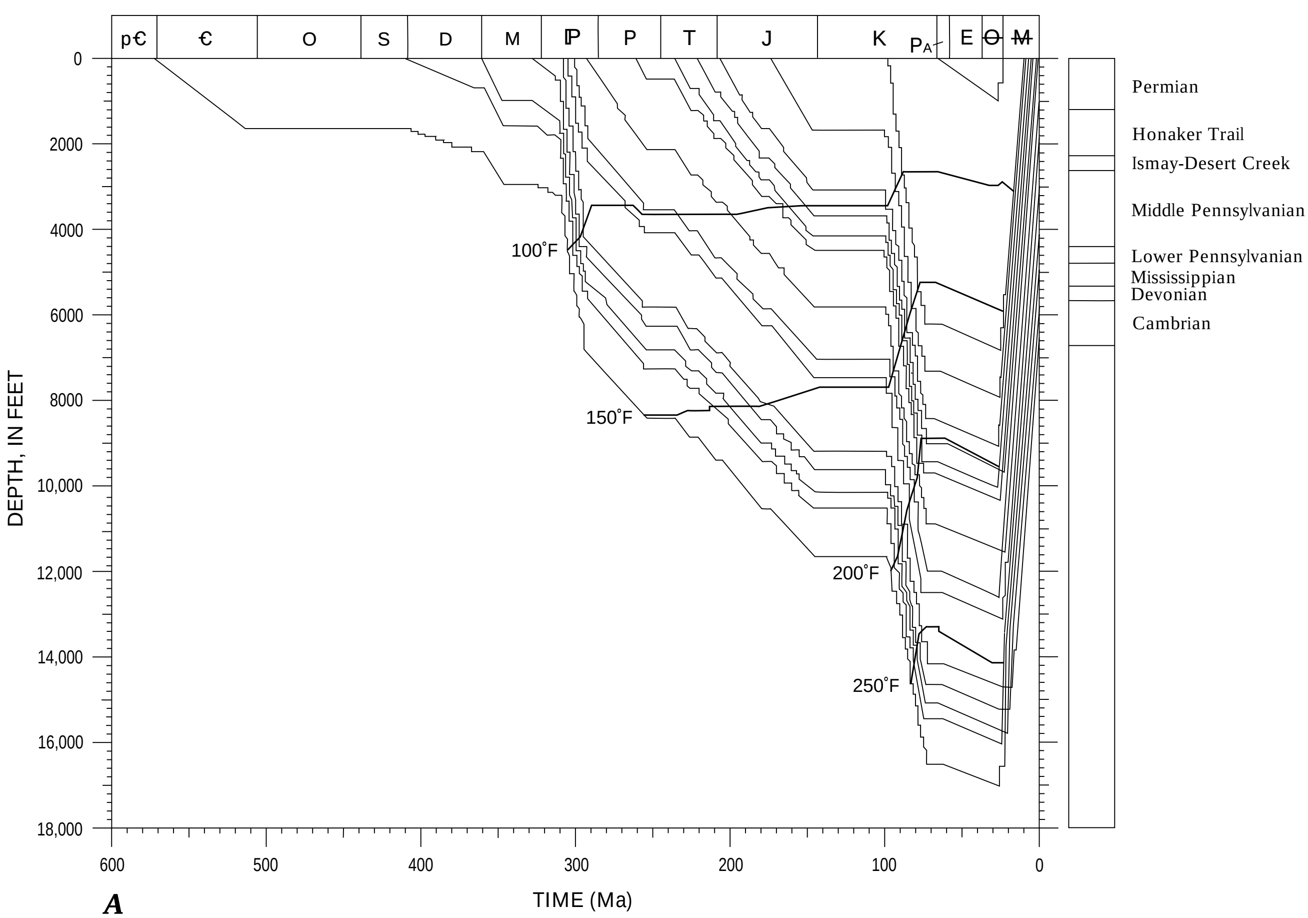
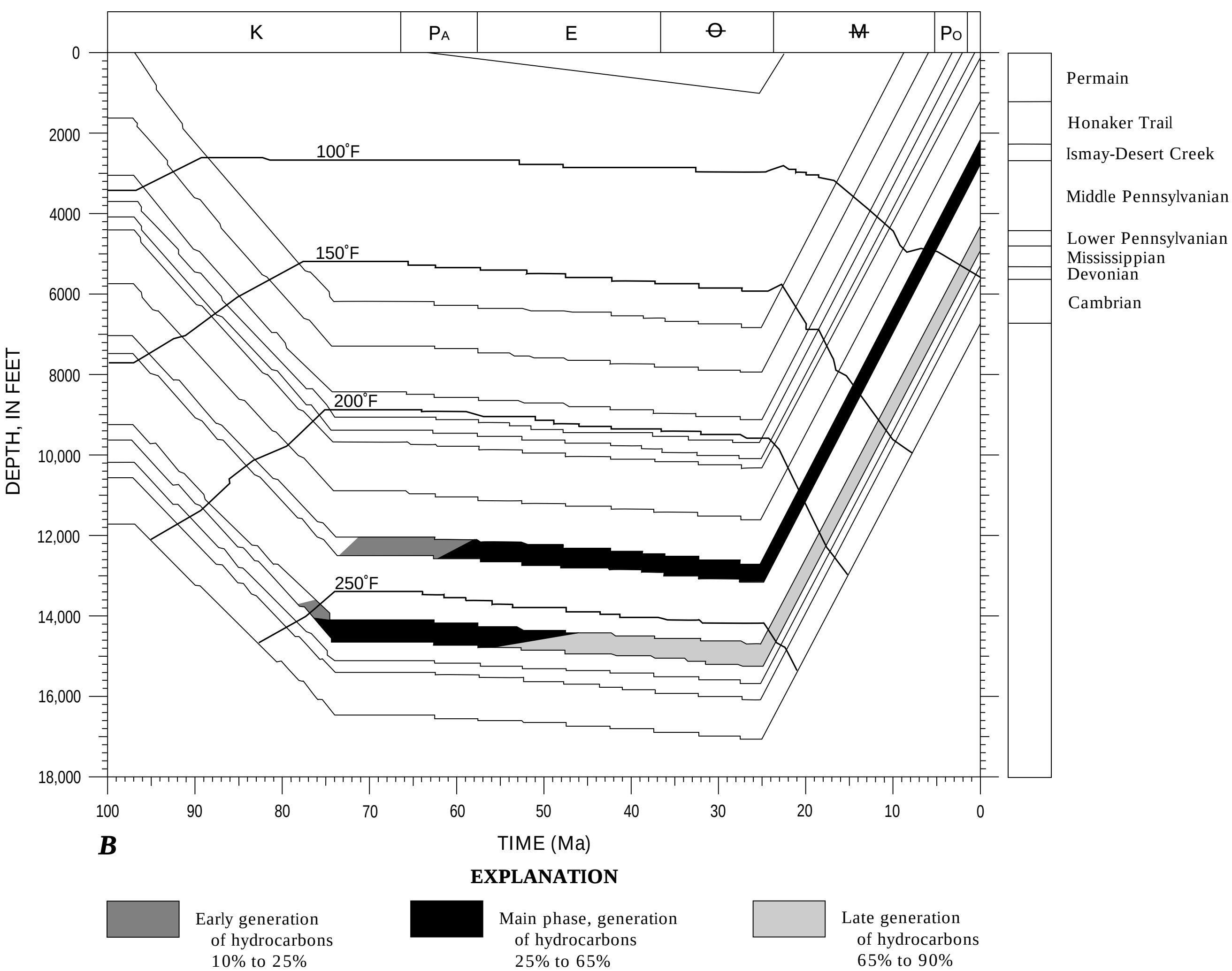


Figure 13. Burial, thermal, and petroleum-generation model of the area near the confluence of the Green and Colorado Rivers (see figs. 1 and 2). *A*, Cambrian through present. *B*, Expanded time scale illustrating 100 Ma to present.

table 3), indicating a time of structural and sedimentological quiescence. An estimated 5,800 ft of Cretaceous rocks were once present in the area of the Monument upwarp (Molenaar, 1981; R.S. Zech, written commun., 1994) representing thick, rapid deposition in the Cretaceous interior seaway. Because of igneous activity that occurred in the southern part of the Paradox Basin from about 32 to 25 Ma, we estimate that 1,000 ft of Tertiary volcaniclastics were deposited in the area. Beginning at approximately 25 Ma and continuing until present time, uplift and subsequent erosion have removed Tertiary, Cretaceous, Jurassic, Triassic, and uppermost Permian strata from the Monument upwarp area (fig. 12).

PI values for the Ismay–Desert Creek interval and Cane Creek cycle are 0.10 and about 0.20, respectively, in the Monument upwarp area (figs. 10, 11). In this area, the Ismay–Desert Creek interval was buried to a maximum depth of about 13,400 ft at 25 Ma, and the Cane Creek cycle was buried to a maximum depth of about 14,300 ft (fig. 12). Maximum maturity was achieved at about 25 Ma. A constant heat flow of 40 mWm^{-2} for the entire burial and thermal history is required to match the measured maturity values for the area. It is possible that an elevated heat flow associated with igneous activity during the Tertiary occurred; however, the thermal effects from intrusive bodies are generally localized, and there are no intrusive bodies in the immediate area. An increased heat flow in the Monument upwarp area during the Tertiary results in thermal maturity values that are too high for this area. The isotherms calculated using the above heat-flow value illustrate temperature variations with depth and through time (fig. 12).

The petroleum-generation model for the Monument upwarp area (fig. 12*B*) indicates that early oil generation from the Ismay–Desert Creek interval began at about 74 Ma. Significant oil generation, enough for accumulation and migration (PI=0.10), began later, at about 45 Ma, and likely lasted until the time of uplift, erosion, and subsequent cooling at 25 Ma. Oil generation from the Cane Creek cycle began earlier than for the Ismay–Desert Creek interval due to greater depth of burial associated with deposition of Middle Pennsylvanian strata. Early oil generation from the Cane Creek began at about 77 Ma, and significant oil generation began at about 69 Ma (fig. 12*B*). As with the Ismay–Desert Creek interval, oil generation from the Cane Creek lasted until 25 Ma.



CONFLUENCE OF THE GREEN AND COLORADO RIVERS

The area around the confluence of the Green and Colorado Rivers (figs. 1, 2) has experienced a similar burial history as the Monument upwarp (compare figs. 12*A* and 13*A*); however, in the confluence area, the maturity of the Ismay–Desert Creek interval and the Cane Creek cycle is slightly higher (figs. 10, 11). The Pennsylvanian section (especially the Middle Pennsylvanian) in the confluence area is thicker than that in the Monument area, and the Permian sections are similar. Triassic and Jurassic rocks are thinner in the confluence area (fig. 6, table 3), and thicknesses of Cretaceous and Tertiary strata are the same as used for the Monument upwarp area (5,800 ft and 1,000 ft, respectively). Beginning at approximately 25 Ma and continuing until the present, erosion has removed Tertiary, Mesozoic, and uppermost Permian rocks from the confluence area.

Production-index values for the Ismay–Desert Creek interval are near 0.20, and, for the Cane Creek cycle, they are about 0.25—higher than indices for the Monument upwarp area (figs. 10, 11). In the confluence area, at maximum burial at 25 Ma, the Ismay–Desert Creek interval was buried to about 13,000 ft and the Cane Creek cycle to about 14,200 ft. Although overall depth of burial is similar to that for the Monument upwarp area, the Middle Pennsylvanian and Honaker Trail sections are sufficiently thicker in the confluence area to have an effect on the maturity of the Ismay–Desert Creek interval and the Cane Creek cycle at maximum burial.

A constant heat flow of 42 mWm^{-2} for the entire burial and thermal history is required to match the measured maturity values for the area. Similar to the Monument upwarp area, it is possible that an elevated heat flow associated with igneous activity during the Tertiary occurred; however, there are no intrusions in the immediate area. Raising the heat flow would result in an excessively high maturity for this area. The isotherms calculated using the heat-flow value of 42 mWm^{-2} illustrate temperature variations with depth and through time (fig. 13).

The combination of (1) a thicker Pennsylvanian section for the confluence area than in the areas to the southwest in

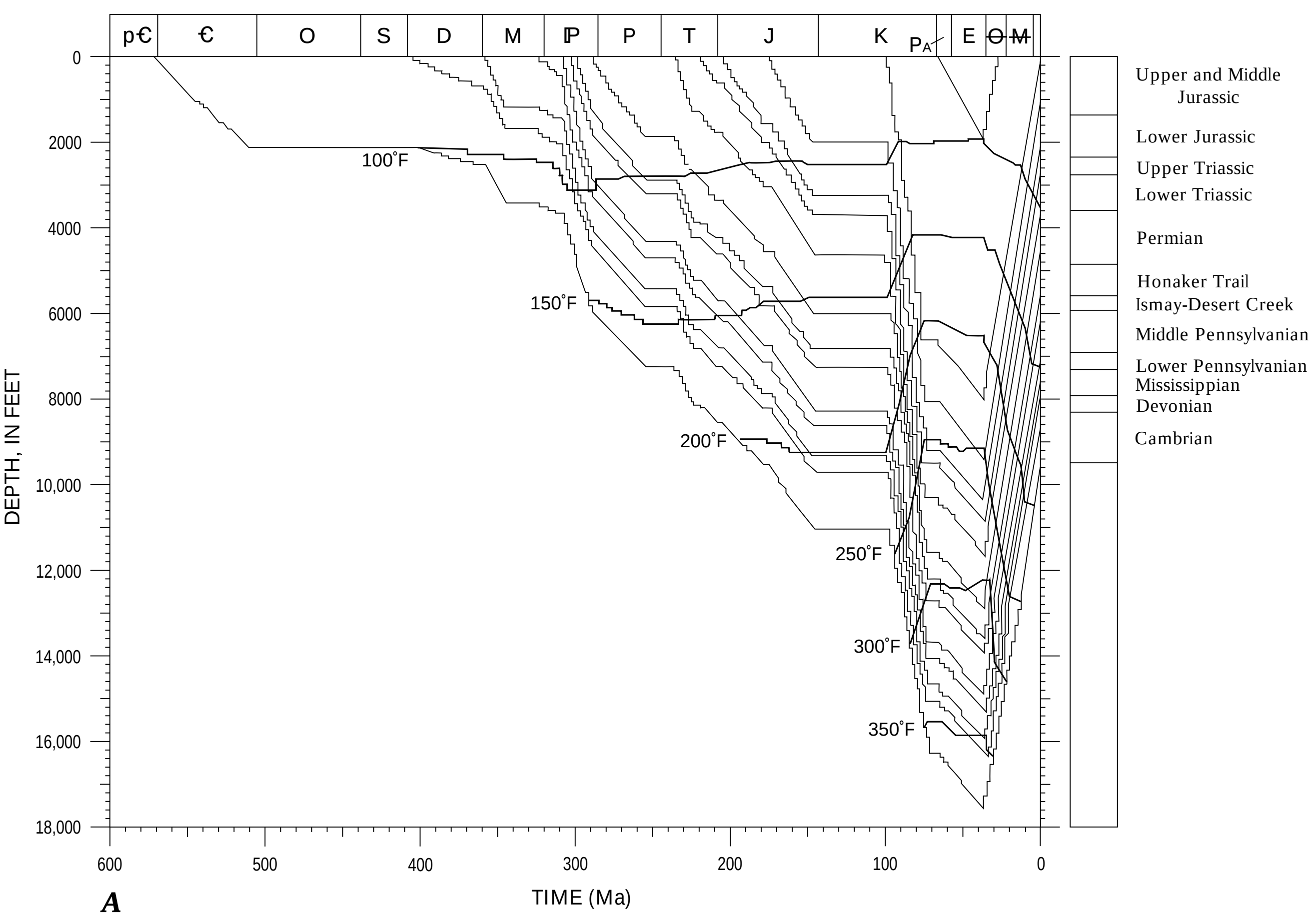


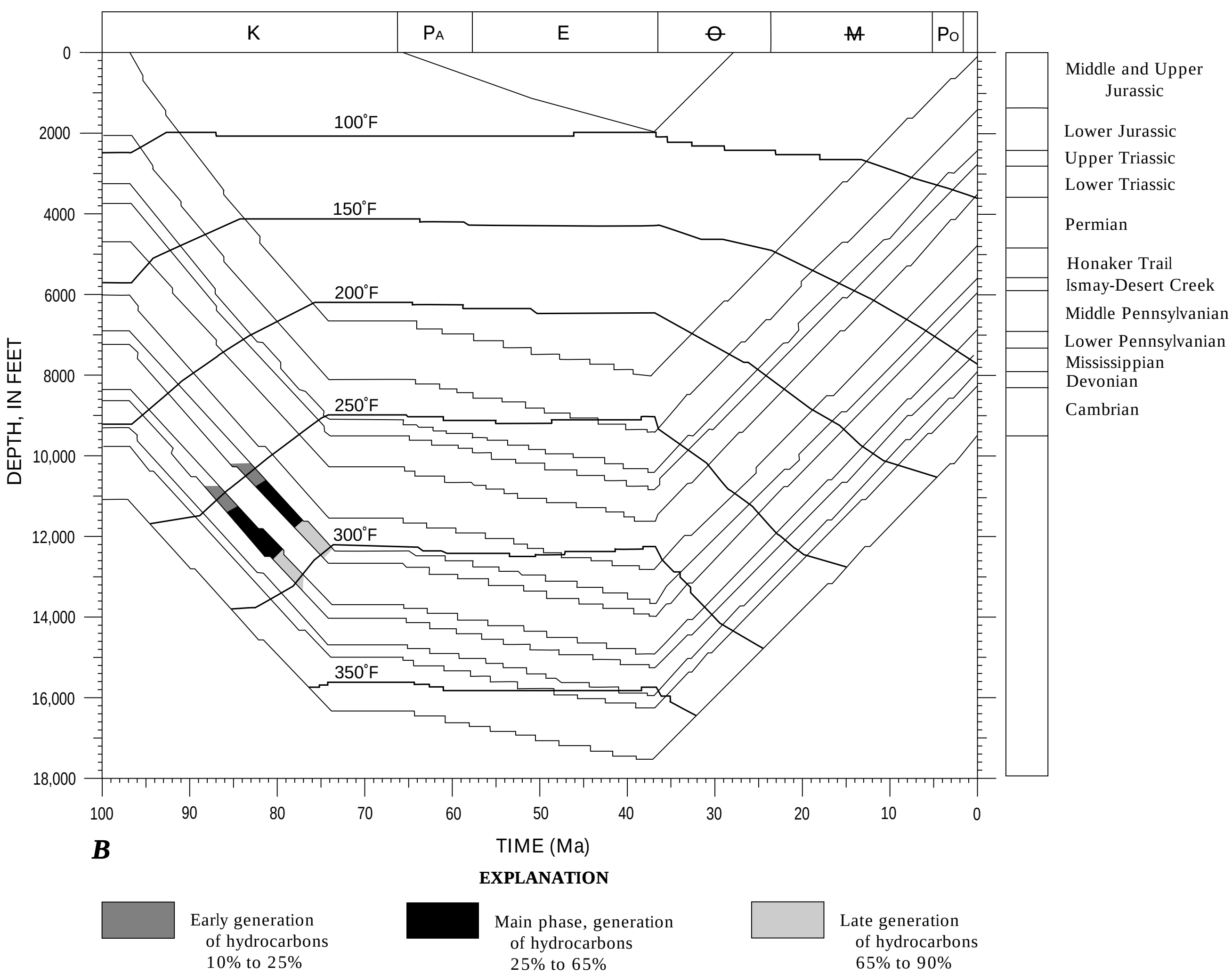
Figure 14. Burial, thermal, and petroleum-generation model of the area near Green River, Utah (see figs. 1 and 2). *A*, Cambrian through present. *B*, Expanded time scale illustrating 100 Ma to present.

conjunction with (2) a slightly higher heat flow has resulted in an earlier timing for oil generation from the Ismay–Desert Creek interval and the Cane Creek cycle. The petroleum-generation model for the area around the confluence of the Green and Colorado Rivers (fig. 13*B*) indicates that early oil generation from the Ismay–Desert Creek interval began at about 75 Ma. Significant oil generation, enough for accumulation and migration (PI=0.10), began at about 60 Ma and likely lasted until the time of uplift at 25 Ma. Oil generation from the Cane Creek cycle began before oil generation from the Ismay–Desert Creek interval due to greater depth of burial associated with deposition of Middle Pennsylvanian strata. Early oil generation from the Cane Creek began at about 80 Ma and significant oil generation at about 75 Ma (fig. 13*B*). The petroleum-generation model indicates that temperatures and maturities were sufficiently high (PI >0.20, equivalent to about 0.80–0.90 percent R_o) for some gas generation from kerogen in the Cane Creek cycle beginning at 57 Ma. As with the Ismay–Desert Creek interval, oil and gas generation from the Cane Creek lasted until uplift, erosion, and subsequent cooling after 25 Ma.

GREEN RIVER, UTAH

The area around the town of Green River, Utah, is one of the most thermally mature areas in the Paradox Basin (figs. 10, 11). Three factors play integral roles in determining this high level of thermal maturity: (1) a relatively thick Tertiary section (eroded), (2) less erosion than other parts of the basin, and (3) a high heat flow. The petroleum-generation history for this area shows that source rocks in the Paradox Formation were in the oil window for only a short duration before overmaturity and destruction.

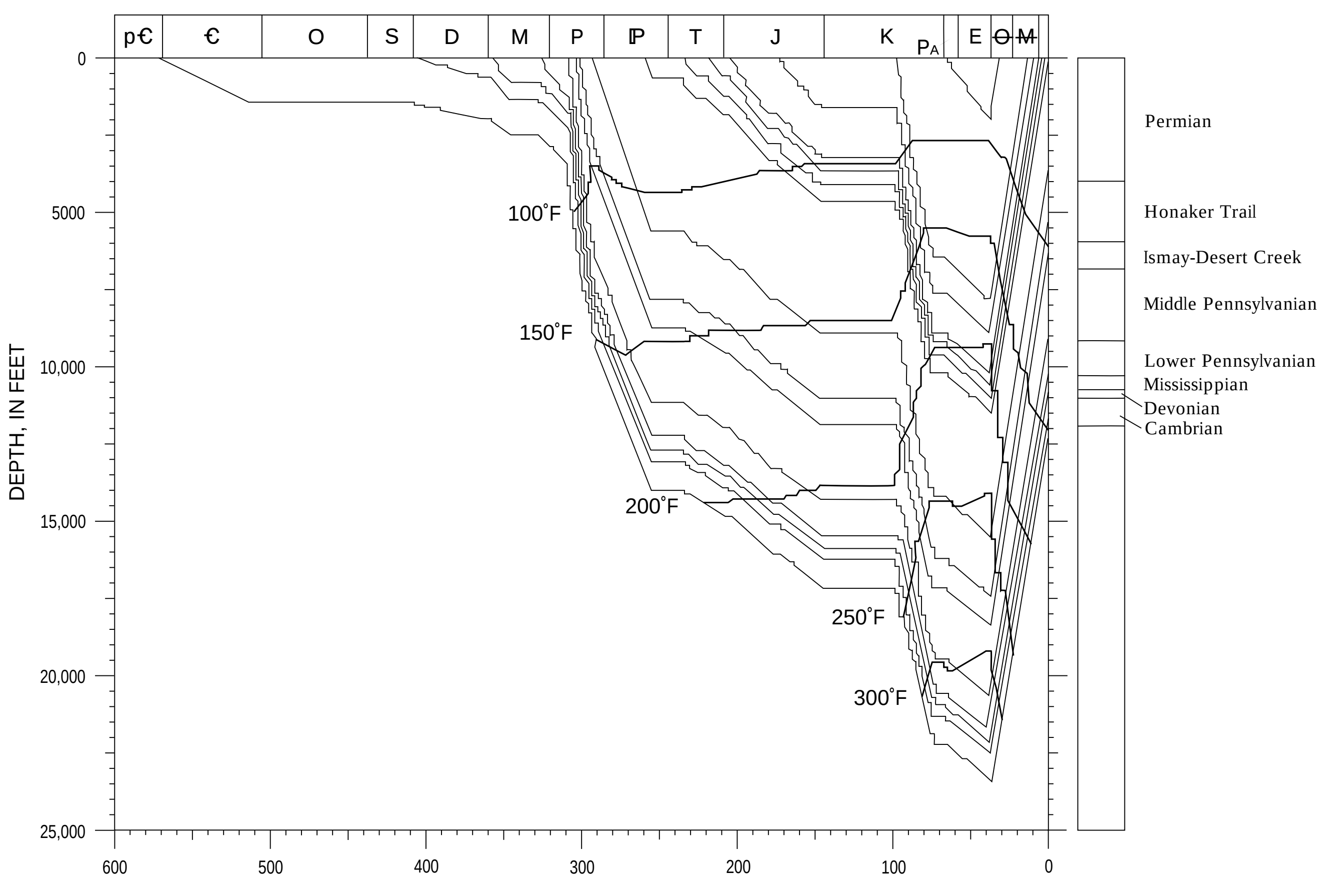
During late Paleozoic time, the area around Green River, Utah, was in the western part of the Paradox Basin on a fairly stable shelf or platform, and a relatively thin Pennsylvanian and Permian section was deposited (fig. 5, table 3). The Triassic and Jurassic section is relatively thin in this area; however, it thickens dramatically to the southeast (fig. 6). A thick Cretaceous section of 6,000 ft is estimated to have covered this area, similar to those thicknesses preserved at the Book Cliffs immediately to the north. As discussed previously, Paleocene and Eocene strata are also thought to have once been present in this area. We assume



that 2,000 ft of Tertiary rocks (North Horn and Green River Formation equivalents) were deposited in this area; however, this may be a conservative estimate. In the area around Green River, Utah, uppermost Jurassic strata are present on the surface. We estimate that about 8,000 ft of erosion occurred here, much less than in most of the Paradox Basin. Therefore, source rocks in the Green River, Utah, area were subjected to a greater burial depth and temperature for a longer period of time.

In the Green River, Utah, area, production indices for the Ismay–Desert Creek interval are about 0.60, and production indices for the Cane Creek cycle are greater than 0.60. During maximum burial at about 37 Ma, the Ismay–Desert Creek interval was buried to a depth of about 14,000 ft and the Cane Creek was buried to about 15,400 ft (fig. 14). Because there are no intrusive rocks in the area, a constant heat flow of 53 mWm^{-2} was used to match the measured maturity values. Except for the Hermosa, Colo., area, which was influenced by Tertiary igneous activity, the Green River, Utah, area has the highest heat flow of the areas discussed in this report. The isotherms in figure 14 illustrate the high temperatures with depth and time for this area.

Petroleum generation in the Ismay–Desert Creek interval and Cane Creek cycle is illustrated by figure 14*B*. Oil generation in the Ismay–Desert Creek interval began at about 85 Ma, and significant oil generation occurred at about 82 Ma. Due to the high temperatures, oil began to be thermally cracked to gas at about 78 Ma, and the upper limit for petroleum preservation occurred at about 74 Ma. Thus, the Ismay–Desert Creek was only in the petroleum-generation window for about 11 m.y. The onset of oil generation in the Cane Creek cycle began at about 89 Ma, and significant oil generation occurred at about 85 Ma. Again, due to the high temperatures, oil began to crack to gas at about 81 Ma, and the upper limit for petroleum preservation occurred at about 77 Ma. The Cane Creek cycle was only in the petroleum-generation window for about 12 m.y. Comparison of this petroleum-generation history to that of the Monument upwarp (fig. 12*B*) and the confluence area (fig. 13*B*), in both of which the Ismay–Desert Creek interval and Cane Creek cycle were in the petroleum-generation window for more



A

Figure 15. Burial, thermal, and petroleum-generation model of the area near Moab, Utah (see figs. 1 and 2). *A*, Cambrian through present. *B*, Expanded time scale illustrating 200 Ma to present.

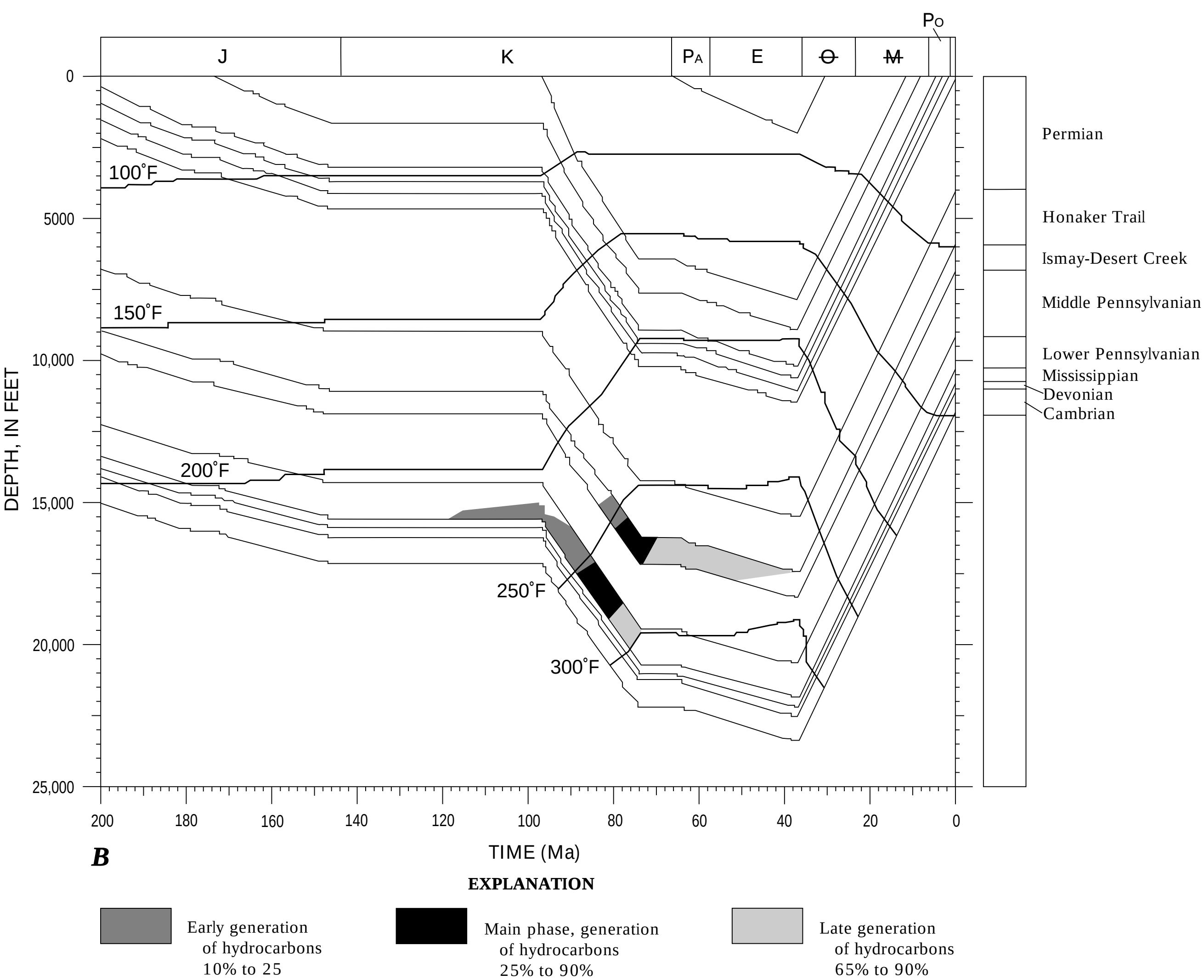
than 65 m.y., shows the importance of temporal relationships between hydrocarbon generation, migration and entrapment, and structural trap development.

MOAB, UTAH

The area around the town of Moab, Utah, is in the structurally deeper part of the Paradox Basin. In late Paleozoic time, this part of the basin was rapidly subsiding, and thick sequences of Pennsylvanian and Permian strata were deposited (fig. 5, table 3). During Triassic and Jurassic time, only a moderate 3,175 ft of strata were deposited in this part of the basin; however, to the north, thousands of feet more sediment was deposited (fig. 6). We estimate that 5,900 ft of Cretaceous rocks and 2,000 ft of Paleocene and Eocene rocks were once present in this part of the basin. Beginning at about 37 Ma and continuing until the present, uplift and erosion have removed approximately 11,575 ft of rocks from the area, leaving Permian rocks at the surface (fig. 15). It should be noted that thicknesses of Pennsylvanian and Permian strata, as well as amounts of erosion and rocks present at the surface, change very rapidly in this area. Consequently, depending on the exact location, the geologic history may be quite different.

In the Moab area, production indices for the Ismay–Desert Creek interval are slightly less than 0.30; for the Cane Creek cycle, production indices are about 0.35. During maximum burial at about 37 Ma, the Ismay–Desert Creek interval was buried to about 18,250 ft and the Cane Creek cycle to 22,000 ft. A constant heat flow of 40 mWm^{-2} for the entire burial and thermal history is required to match the measured maturity values for the area. Elevated heat flow in the Tertiary in conjunction with igneous activity is inappropriate for this area because the nearest intrusive bodies are 15 mi to the east. In addition, an increase in heat flow would result in an excessively high thermal maturity in this area.

The petroleum-generation history illustrated in figure 15*B* indicates that early oil generation from the Ismay–Desert Creek interval began at about 82 Ma. Significant oil generation began at 79 Ma, and primary gas generation from kerogen, as well as gas generation from



thermally cracked oil, began at 74 Ma. The upper limit for petroleum preservation within Ismay–Desert Creek interval occurred between 50 (lower part) and 40 (upper part) Ma. Early oil generation from the Cane Creek cycle began at about 120 Ma—much earlier than for the previously mentioned areas because of the much thicker Middle Pennsylvanian section in the Moab area. Significant oil generation from the Cane Creek began at 90 Ma, and primary gas generation from kerogen, as well as gas generation from thermally cracked oil, began at about 80 Ma. The upper limit for petroleum preservation within the Cane Creek occurred at approximately 75 Ma.

LISBON VALLEY AREA, UTAH

The Lisbon Valley area (Lisbon Valley is a northwest-trending valley, which is located approximately 22 mi north-northwest of Monticello, Utah) is similar to the Moab, Utah, area in that it is in the structurally deeper part of the Paradox Basin (fig. 5). During the Pennsylvanian and Permian, 11,950 ft of strata was deposited around Lisbon Valley (fig. 5, table 3). Especially important to the thermal and petroleum-generation history of the Cane Creek cycle are the 4,900 ft of Middle Pennsylvanian rocks. Triassic rocks are thin in the Lisbon Valley area, and a modest 2,050 ft of Jurassic rocks are present (fig. 6). We estimate that 6,000 ft of Cretaceous rocks (Molenaar, 1981; R.S. Zech, written commun., 1994) and 1,000 ft of Tertiary rocks were once present in the Lisbon Valley area. Paleocene North Horn Formation and Eocene Green River Formation equivalents probably did not extend this far south; however, some Tertiary strata composed of volcaniclastic and ash beds were likely deposited here. Beginning at about 25 Ma and continuing until the present, uplift and erosion have stripped approximately 13,350 ft of strata from the area, exposing Upper Pennsylvanian rocks at the surface (fig. 16). The Lisbon Valley area has experienced the greatest amount of erosion of the six areas studied in this report and is among those areas with the most erosion in the entire Paradox Basin.

The production index for the Ismay–Desert Creek interval in Lisbon Valley is 0.30, and, for the Cane Creek cycle, it is greater than 0.60 (figs. 10, 11). The large difference in

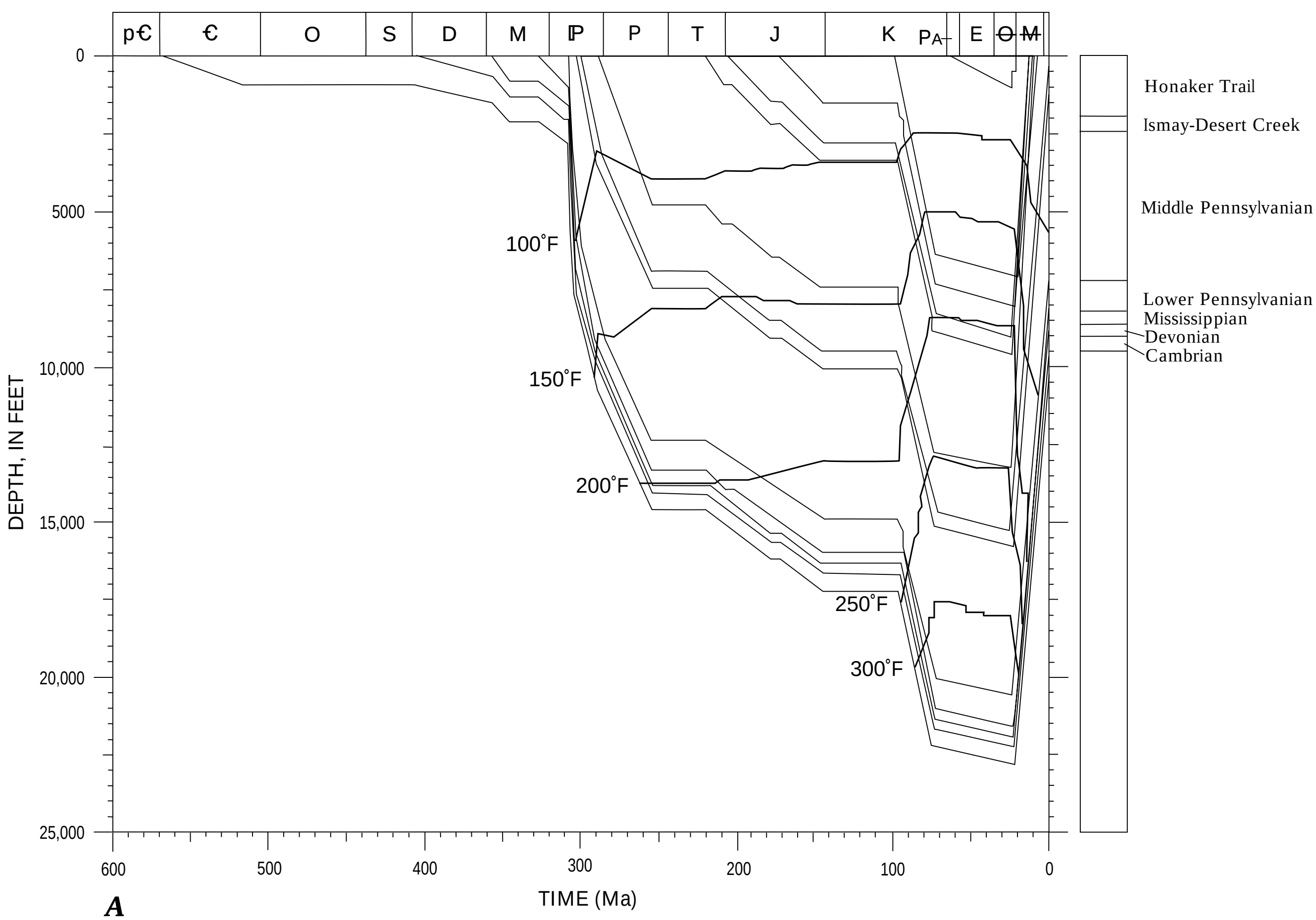


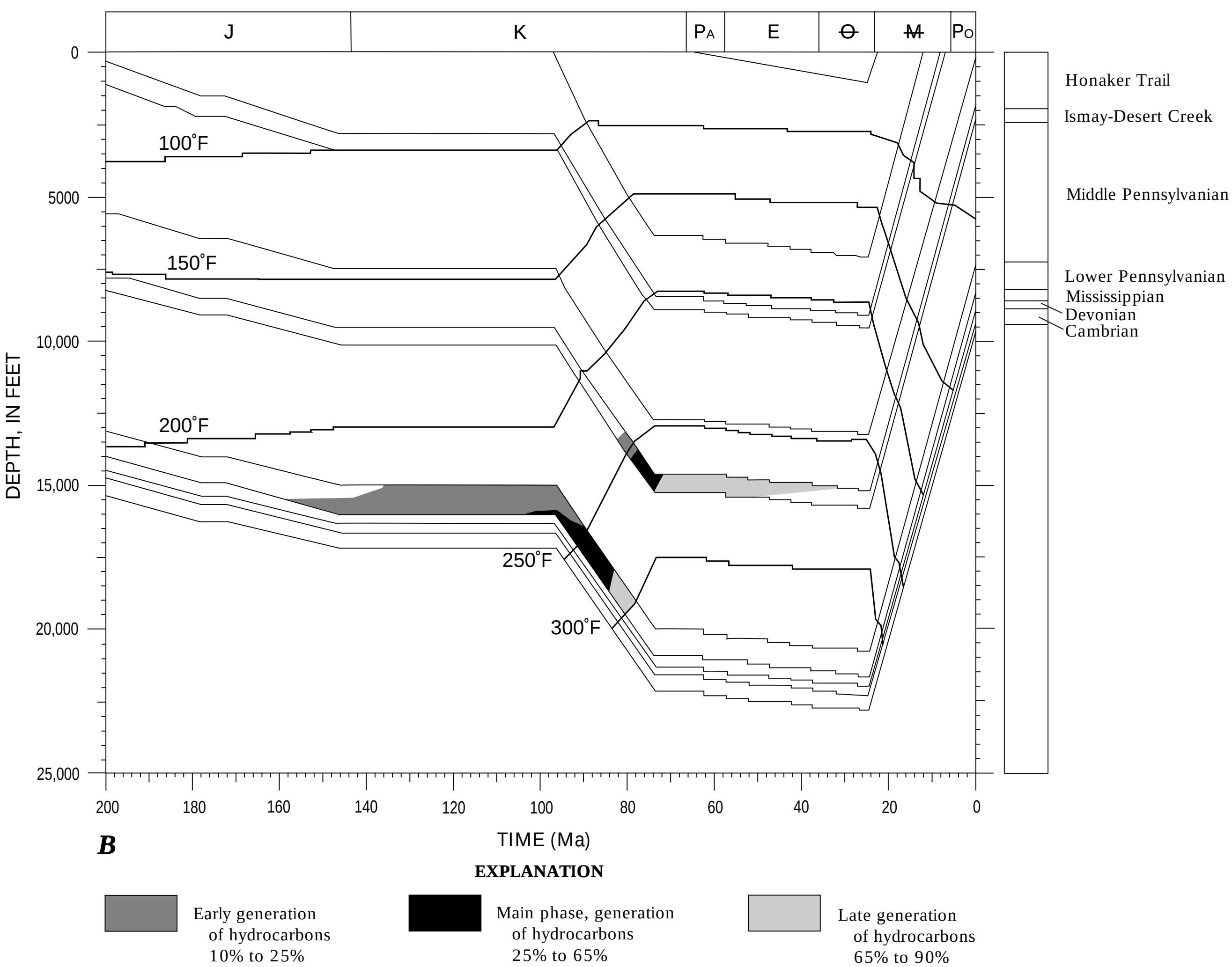
Figure 16. Burial, thermal, and petroleum-generation model of the Lisbon Valley, Utah, area (see fig. 2 for location of Lisbon Valley anticline). *A*, Cambrian through present. *B*, Expanded time scale illustrating 200 Ma to present.

production index, and the reason why the Cane Creek is so much more mature than the Ismay–Desert Creek, is the thick Middle Pennsylvanian section (4,900 ft) that overlies the Cane Creek cycle. At 25 Ma, in Lisbon Valley, the Ismay–Desert Creek interval reached a maximum burial depth of 15,750 ft (fig. 16), whereas the Cane Creek was buried to a maximum depth of approximately 21,500 ft (fig. 16). A constant heat flow of 44 mWm^{-2} for the entire burial and thermal history is required to match the calculated maturity with the measured maturity for Lisbon Valley. As for most areas of the basin, raising the heat flow in the Tertiary for Lisbon Valley results in excessively high levels of thermal maturity. The fact that the Tertiary La Sal Mountain intrusive rocks are only 10 mi north of Lisbon Valley demonstrates the extremely localized effect of heating from these igneous bodies.

Due to the thicker Pennsylvanian and Permian section and the slightly higher heat flow in Lisbon Valley, oil generation from the Ismay–Desert Creek interval and Cane Creek cycle began earlier here than in the Moab area. To the east and northeast of Lisbon Valley, the Pennsylvanian and Permian section thickens rapidly, and one would expect petroleum generation to begin earlier and the upper limit for petroleum preservation to occur earlier. The petroleum-generation history illustrated in figure 16*B* shows that early oil generation from the Ismay–Desert Creek began at around 82 Ma, similar to the Moab area. Significant oil generation began at 79 Ma, and gas generation from kerogen as well as gas generation from cracked oil began at 74 Ma, again similar to the Moab area. The upper limit for petroleum preservation within Ismay–Desert Creek occurred between 42 (lower part) and 32 (upper part) Ma. Early oil generation from the Cane Creek cycle began at around 156 Ma—much earlier than for the previously mentioned areas, again because of the thicker Middle Pennsylvanian section. Significant oil generation from the Cane Creek began at 100 Ma, and gas generation from kerogen as well as gas generation from cracked oil began at about 84 Ma. The upper limit for petroleum preservation within the Cane Creek occurred at approximately 78 Ma (fig. 16*B*).

HERMOSA, COLORADO

Of the six areas studied for this report, the Hermosa, Colo., area (located approximately 10 mi north of Durango, Colo.) is unique in that it has undergone the least amount of



Cambrian through Jurassic burial in the Paradox Basin, yet it is one of the most thermally mature. Figures 4 and 6 and table 3 illustrate the relatively thin sub-Pennsylvanian, Triassic, and Jurassic units in the Hermosa area. Figure 5 shows Pennsylvanian and Permian thickness trends in the southeastern part of the basin near Hermosa, Colo. Thicknesses of Pennsylvanian strata were also obtained from measured sections near Hermosa Mountain, approximately 10 mi north of Durango, Colo. (Franczyk, 1992, and K.J. Franczyk, oral commun., 1994). By extrapolating from nearby outcrops, we estimate that 6,250 ft of Cretaceous rocks and 2,500 ft of Tertiary rocks (including some volcanics) were once present in the Hermosa area. This represents the thickest Cretaceous and Tertiary section of the six study areas. Beginning at about 25 Ma and continuing until the present time, uplift and erosion have removed approximately 12,550 ft of Permian through Tertiary rocks from the Hermosa area, exposing lowermost Permian rocks at the surface (fig. 17).

In the Hermosa, Colo., area, vitrinite reflectance values of 1.58 percent for the Ismay–Desert Creek interval and 1.62 and 1.52 percent for the Cane Creek cycle indicate that this is one of the most mature areas in the Paradox Basin. At about 25 Ma, the Ismay–Desert Creek interval was buried to a maximum depth of 13,700 ft and the Cane Creek cycle was buried to about 15,500 ft. Depth of burial in conjunction with present-day heat-flow values cannot account for the high level of thermal maturity measured in this area. Several igneous bodies have intruded this part of the basin, and, although they are not exposed at Hermosa, intrusions may underlie the area. In order to match the modeled maturity with the measured vitrinite reflectance data, we must assume a variable heat flow: 600–30 Ma, 45 mWm^{-2}; 30–25 Ma, 63 mWm^{-2}; and 25–0 Ma, 50 mWm^{-2}. Heat flow in the Tertiary was sufficiently high to mask the previous thermal maturity achieved during normal burial and heat flow. Isotherm lines shown in figure 17 illustrate the increase in temperature associated with high heat flow from 30 to 25 Ma.

The petroleum-generation history for the Ismay–Desert Creek interval and Cane Creek cycle in the Hermosa area is shown in figure 17*B*. Petroleum generation, accumulation, and possible migration predated the increase in heat flow in Tertiary time; however, the high temperatures between 30 and 25 Ma would have thermally destroyed any liquid hydrocarbons still present in the area. Early oil generation from the

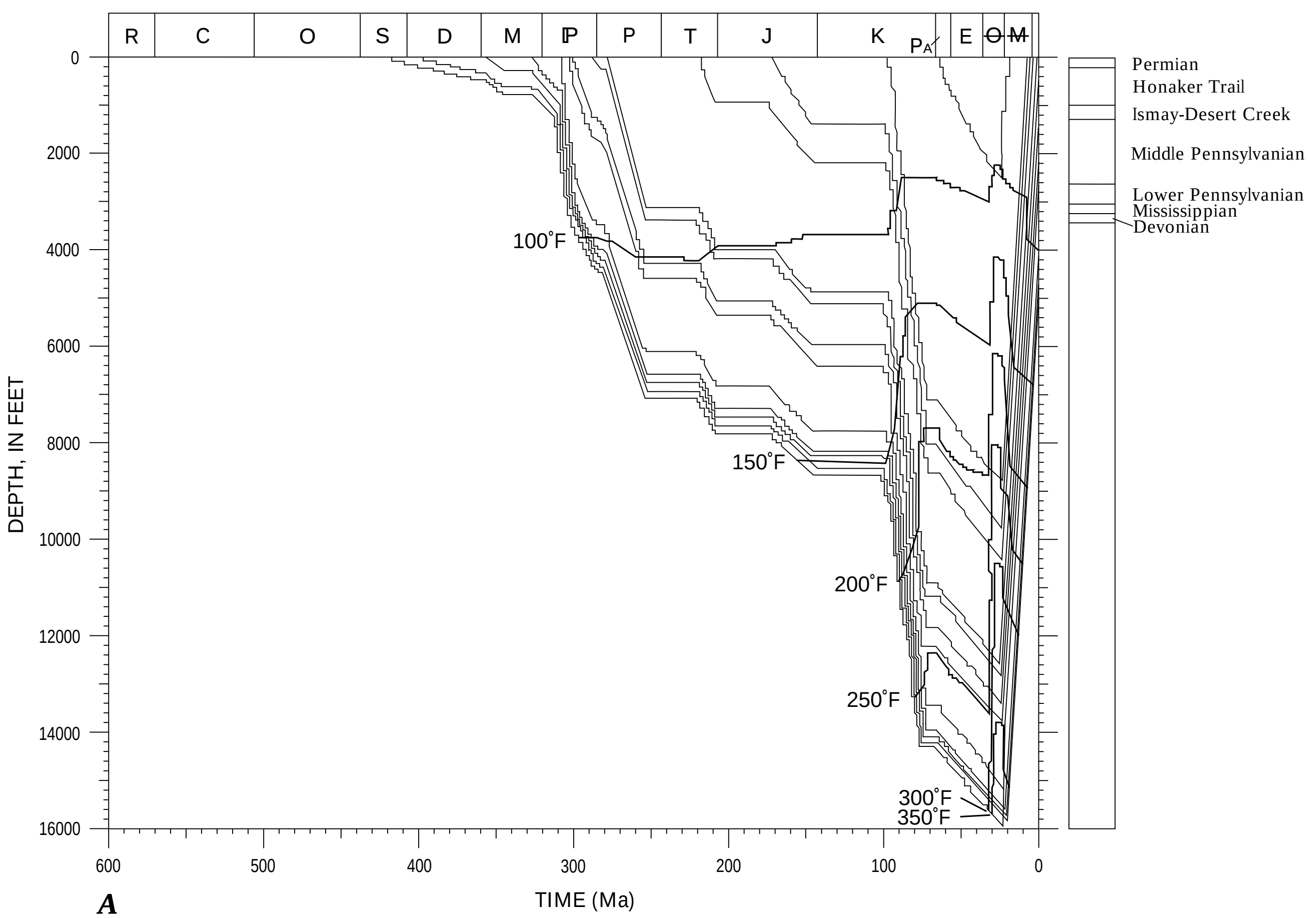


Figure 17. Burial, thermal, and petroleum-generation model of the area near Hermosa, Colo. (this area is represented by the large dot immediately north of Durango, Colo., on fig. 1). *A*, Cambrian through present. *B*, Expanded time scale illustrating 200 Ma to present.

Ismay–Desert Creek began at about 74 Ma, and significant oil generation began at about 72 Ma. Gas generation from kerogen itself, as well as gas generation from cracked oil, began at 34 Ma, but, because of the increase in heat flow in Tertiary time, temperatures quickly exceeded the preservation limit and most petroleum was destroyed at 33 Ma (fig. 17*B*). It should be noted that the preservation limit for dry gas has been postulated to occur at higher temperatures and thermal maturities (R_o as high as 4.0 percent; Waples, 1980) than those in the Hermosa area. Thus, it is possible that gas may still be present in this part of the basin. Early oil generation from the Cane Creek cycle began at about 78 Ma, and significant oil generation began at about 76 Ma. Gas generation from kerogen itself, as well as gas generation from cracked oil, began at about 66 Ma, and the upper limit for petroleum preservation within Cane Creek occurred at approximately 34 Ma. Generation, accumulation, migration, and even the upper limits for preservation of petroleum from the Cane Creek cycle occurred prior to, and were not affected by, the high heat flow in the Tertiary at 30 Ma (fig. 17*B*). Similar to the Ismay–Desert Creek interval, however, Cane Creek gas is still likely preserved in reservoirs in the Hermosa area.

DISCUSSION AND SUMMARY

The petroleum potential of the Ismay–Desert Creek interval and Cane Creek cycle of the Middle Pennsylvanian Paradox Formation of the Paradox Basin is directly related to source rock quality and thermal maturity. Thermal maturity, in turn, is directly related to the structural, burial, and heat-flow history. Samples from the Ismay–Desert Creek and Cane Creek indicate that these strata contain good to excellent source rocks (table 1). The majority of samples from both horizons have total organic carbon values of 0.50 percent or more, and some values are as high as 11.0 percent. The Ismay–Desert Creek interval contains some type I organic matter, but mainly contains types II and III organic matter, which are sources for both oil and gas. The Cane Creek cycle contains types I, II, and III organic matter, which are sources for oil and gas. For both intervals, samples near

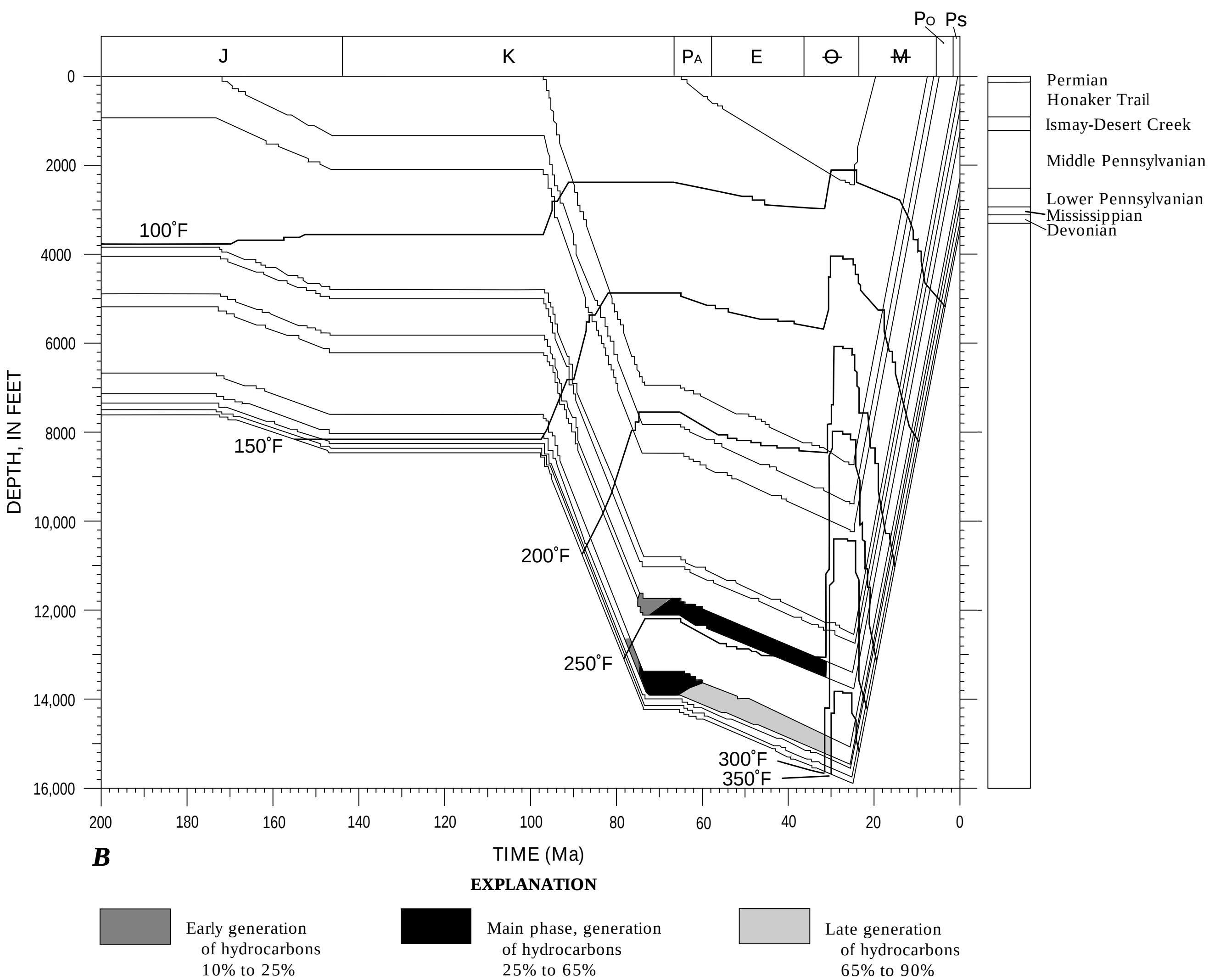


Table 4. Heat-flow values used for the burial and thermal models, and timing of petroleum generation from the Ismay–Desert Creek interval and Cane Creek cycle for the six areas studied in the Paradox Basin Utah and Colorado.

[The six areas studied are shown by large dots on figs. 1, 10, and 11. Key used for ages of timing of petroleum generation: early oil generation, significant oil generation, gas generation (from either kerogen or thermal cracking of oil), and upper limit for petroleum preservation]

	Monument upwarp area	Confluence area	Green River, Utah	Moab, Utah	Lisbon Valley, Utah, area	Hermosa, Colo.
Heat flow						
	40 mWm^{-2} constant	42 mWm^{-2} constant	53 mWm^{-2} constant	40 mWm^{-2} constant	44 mWm^{-2} constant	45 mWm^{-2} 600–30 Ma 63 mWm^{-2} 30–25 Ma 50 mWm^{-2} 25–0 Ma
Timing of petroleum generation (Ma)						
Ismay–Desert Creek interval	74, 45, 25	75, 60, 25	85, 82, 78, 74	82, 79,74, 40	82, 79, 74, 32	74, 72, 34, 33
Cane Creek cycle	77, 69, 25	80, 75, 57, 25	89, 85, 81, 77	120, 90, 80, 75	156, 100, 84, 78	78, 76, 66, 34

the eastern part of the basin have a more terrestrial origin and are likely to be good source rocks for mainly gas.

Thermal maturity for both the Ismay–Desert Creek interval and Cane Creek cycle follows structural and burial trends throughout the basin and increases in a general southwest-to-northeast direction (figs. 10, 11). In Pennsylvanian and Permian time, the eastern part of the basin subsided rapidly, and a thick accumulation of sediments was deposited (fig. 5). As a direct result of greater depth of burial in the eastern part of the basin, thermal maturity increases eastward (figs. 10, 11). In the northernmost part of the basin, near Green River, Utah, the combination of a relatively thicker Tertiary sedimentary sequence and a relatively higher basinal heat flow has resulted in a very high thermal maturity. Although general thermal maturity trends are similar for both the Ismay–Desert Creek interval and the Cane Creek cycle, actual maturity levels are higher for the Cane Creek due to the additional thickness of the Middle Pennsylvanian section. Another significant difference between the two horizons is that, in the south-central to southwestern part of the basin, the Ismay–Desert Creek interval is marginally mature (<0.10 PI) for petroleum generation, but, throughout most of the basin, it is mature and in the petroleum-generation window (0.10 to 0.50 PI). The more mature Cane Creek cycle, however, contains no marginally immature areas; it is mature (>0.10 PI) in the central part of the basin and is overmature and past the petroleum-generation window (>0.50 PI) throughout most of the eastern part of the basin (compare figs. 10, 11).

Estimating paleo heat flow is speculative; however, because the Paradox Basin is in the stable interior of the Colorado Plateau, it is likely that heat flow in the basin has not changed dramatically through time. It is also probable that a large part of the Paradox Basin is at maximum heat flow today. Heat-flow values range from about 40 mWm^{-2} in the interior of the basin to as high as 105 mWm^{-2} on the southeastern periphery of the basin. During the Tertiary, heat flow near intrusions was undoubtedly high; however, the effect on the thermal maturity was extremely localized. Heat-flow values required to match the measured thermal maturity values are consistent with present heat-flow values (table 4). A constant heat flow through time allows a good match for five of the six areas studied: Monument upwarp, 40 $mWm–^{2}$; confluence area, 42 mWm^{-2}; Green River, Utah, 53 mWm^{-2}; Moab, Utah, 40 mWm^{-2}; and Lisbon Valley, 44 mWm^{-2}. The sixth area, Hermosa, Colo., has a high thermal maturity that cannot be accounted for by burial alone and is surrounded by Tertiary igneous bodies. A variable heat flow of 45 mWm^{-2} from 600 to 30 Ma, 63 mWm^{-2} from 30 to 25 Ma, and 50 mWm^{-2} from 25 to 0 Ma is required (table 4).

The relationship between structural, burial, and heat-flow trends in the basin has resulted in differences in the petroleum-generation history for the Ismay–Desert Creek interval and the Cane Creek cycle. For example, in the Monument upwarp area, in the most immature, least deeply buried part of the basin, significant oil generation for the Ismay–Desert Creek interval and the Cane Creek cycle began at about 45 Ma and 69 Ma, respectively. Oil generation likely lasted until uplift, erosion, and subsequent cooling began at about 25 Ma. Thermal maturities sufficiently high for gas generation were probably never achieved in the Monument upwarp area. In contrast, in Lisbon Valley, in the more thermally mature, deeply buried part of the basin, significant oil generation for the Ismay–Desert Creek interval and Cane Creek cycle began at about 79 Ma and 100 Ma, respectively, and extreme temperatures and thermal maturities caused these horizons to pass through the oil window at 74 Ma and 84 Ma, respectively. For the Ismay–Desert Creek interval, gas generation from kerogen, as well as the cracking of oil, began at 74 Ma, and the upper limit for gas preservation occurred at 32 Ma. For the Cane Creek cycle, gas generation from kerogen, as well as the cracking of oil, began at 84 Ma, and the upper limit for gas preservation occurred at 78 Ma.

Timing of petroleum generation and destruction has important implications for the migration and accumulation of oil and gas. Petroleum generated prior to structural movement may never accumulate in structural traps or stratigraphic accumulations and may be lost to the atmosphere through faults and fractures formed during movement. Alternatively, petroleum generated during or after structural movement can accumulate in structural and stratigraphic traps.

The distribution of petroleum in the Paradox Basin is likely related to the type of organic matter in the source rock and to the burial and thermal history (plates 1, 2). Plate 1 shows oil and gas wells producing from the Honaker Trail Formation down through cycle 9 in the Paradox Formation. Also shown are the thermal-maturity production-index contours of the Ismay–Desert Creek interval, which should represent the thermal maturity of the upper part of the Paradox Formation. In general, oil, and associated oil and gas, are in areas where the thermal maturity is in the generation window (PI<0.30–0.40). In the eastern, more mature part of the Paradox Basin where production indices are greater than 0.40 (in the range for cracking of oil to gas), mainly gas is produced. The relationship between thermal maturity and type of hydrocarbon produced is strong; however, all of the gas in the eastern part of the basin may not be cracked oil; a contribution of gas from gas-prone, type III kerogen is probable as well.

Plate 2 shows wells producing from cycle 10 of the Paradox Formation through the Cambrian Lynch Dolomite, as well as production-index contours for the Cane Creek cycle. The contours should be representative of these deeper horizons. Although there are fewer producing wells at these depths in the Paradox Basin, the relationships described for the younger strata still generally hold true. In the northern part of the basin, where production indices are 0.20–0.40, oil only—and oil and gas—are generally produced. In Lisbon Valley, where maturities are greater (in the gas generation range), mainly oil and gas and associated gas are produced. In the southeastern part of the basin where maturities are high, mainly gas only is produced. As previously discussed, gas-prone kerogen has likely contributed to some of the gas in this part of the basin.

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