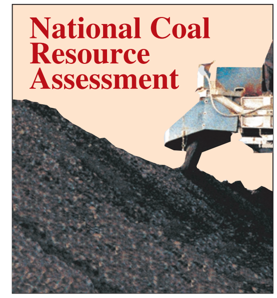
Chapter H

Summary of Cretaceous Stratigraphy and Coal Distribution, Black Mesa Basin, Arizona



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By J. Dale Nations,[1] Robert L. Swift,[1] *and* Henry W. Haven, Jr.[1]

Chapter H *of*

Geologic Assessment of Coal in the Colorado Plateau: Arizona, Colorado, New Mexico, and Utah

Edited by M.A. Kirschbaum, L.N.R. Roberts, *and* L.R.H. Biewick

U.S. Geological Survey Professional Paper 1625–B*

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* This report, although in the USGS Professional Paper series, is available only on CD-ROM and is not available separately

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Figure 1 (Frontispiece). Eastern escarpment of Black Mesa in the Rough Rock area showing upper Mancos Shale and Mesaverde Group. The Rough Rock road is visible in the distance.

Summary of Cretaceous Stratigraphy and Coal Distribution, Black Mesa Basin, Arizona

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Introduction

As a part of the U.S. Geological Survey's National Coal Resource Assessment Project, this report provides a brief summary and guide to the Cretaceous geology and coal deposits of the Black Mesa Basin in northeastern Arizona, which is in the Colorado Plateau region. Information in these reports has been acquired during a National Science Foundation-funded research project (CBM Project) that has been ongoing since 1993 (fig. 2).

The purpose of this research has been to determine the distribution and estimate the volume of coal in Cretaceous rocks of Black Mesa, an erosional remnant in the center of the Black Mesa structural basin (fig. 3). Previous basin-wide estimates of coal volume were made more than 25 years ago and were based mostly on regional stratigraphic information. The data resulting from the work herein described will make possible an improved assessment of the resource.

The report summarizes stratigraphic information from more than 230 locations, from which a regional stratigraphic framework has been developed (fig. 4). The precision of stratigraphic correlation is at the formation level. Coal data are limited (for most of the data points) to total thickness, or even simply presence or absence of coal, at a particular site. These data have allowed only generalized cross sections and isopach maps depicting gross trends of coal occurrence and thickness in the Dakota, Toreva, and Wepo coal-bearing formations in Black Mesa.

A second objective of this work has been to evaluate the potential for coal-bed methane gas production. Due to depth of burial and the rarity of thick coal beds in the coal-bearing strata, only a small portion of Black Mesa coal can be exploited through mining techniques, but the coal-bed methane that may be contained within more deeply buried coal could be produced by standard well-drilling techniques. If present, and if exploration work is allowed, such production might provide a valuable source of energy for local use, and possibly for commercial production.

Field work on the Navajo Nation was conducted under a permit from the Navajo Nation Minerals Department. Any persons wishing to conduct geologic investigations on the Navajo Nation must first apply for, and receive, a permit from the Navajo Nation Minerals Department, P.O. Box 1910, Window Rock, Arizona 86515.

Field work on the Hopi Tribal Land was conducted under a permit from the Chairman of the Hopi Tribe. Any persons wishing to conduct geologic investigations on the Hopi Reservation must receive permission by applying to the Office of Mining and Mineral Resources, The Hopi Tribe, P.O. Box 123, Kykotsmovi, Arizona 86039.

Acknowledgments

The research for this paper was supported since August 1993 by four grants from the National Science Foundation and one from the Mobil Corporation. Continuation of the work was funded in 1997 by the U.S. Geological Survey under the National Coal Resources Data System Program (NCRDS). The primary grant was entitled RUI: "Student-Based Facies Analysis and Determination of Coalbed Methane Potential of Cretaceous Coal-Bearing Rocks, Navajo and Hopi Reservations" (CBM Project). Drafting help was provided by Marin Popov and Chris French.

Location, Physiography, and Structure of Black Mesa Basin

Black Mesa is located in the southwestern part of the Colorado Plateau Region and occupies parts of Navajo, Apache, and Coconino Counties of northeastern Arizona (fig. 5). The mesa lies entirely within the Navajo and Hopi Reservations, between the towns of Chinle, Kayenta, Tuba City, and Winslow, Arizona. Black Mesa is a physiographic mesa in the center of the Black Mesa structural basin, which is bounded by the Kaibab uplift to the west, the Defiance uplift to the

Figure 2. CBM Project field crew planning day's activity.

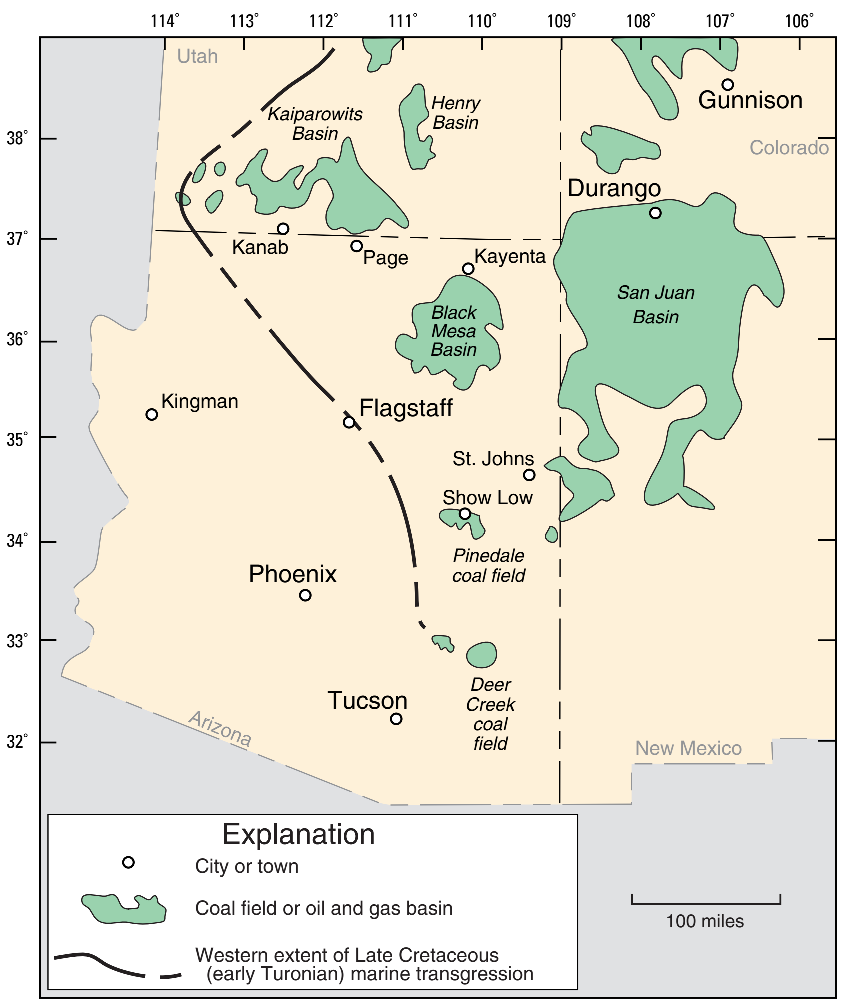

Figure 3. Map of Four Corners area showing maximum western extent of Late Cretaceous marine transgression (dashed line; modified from Cobban and Hook, 1984) and location and extent of coal fields (Arizona portion modified from Peirce and Wilt, 1970). Outlines of coal fields are approximately drawn.

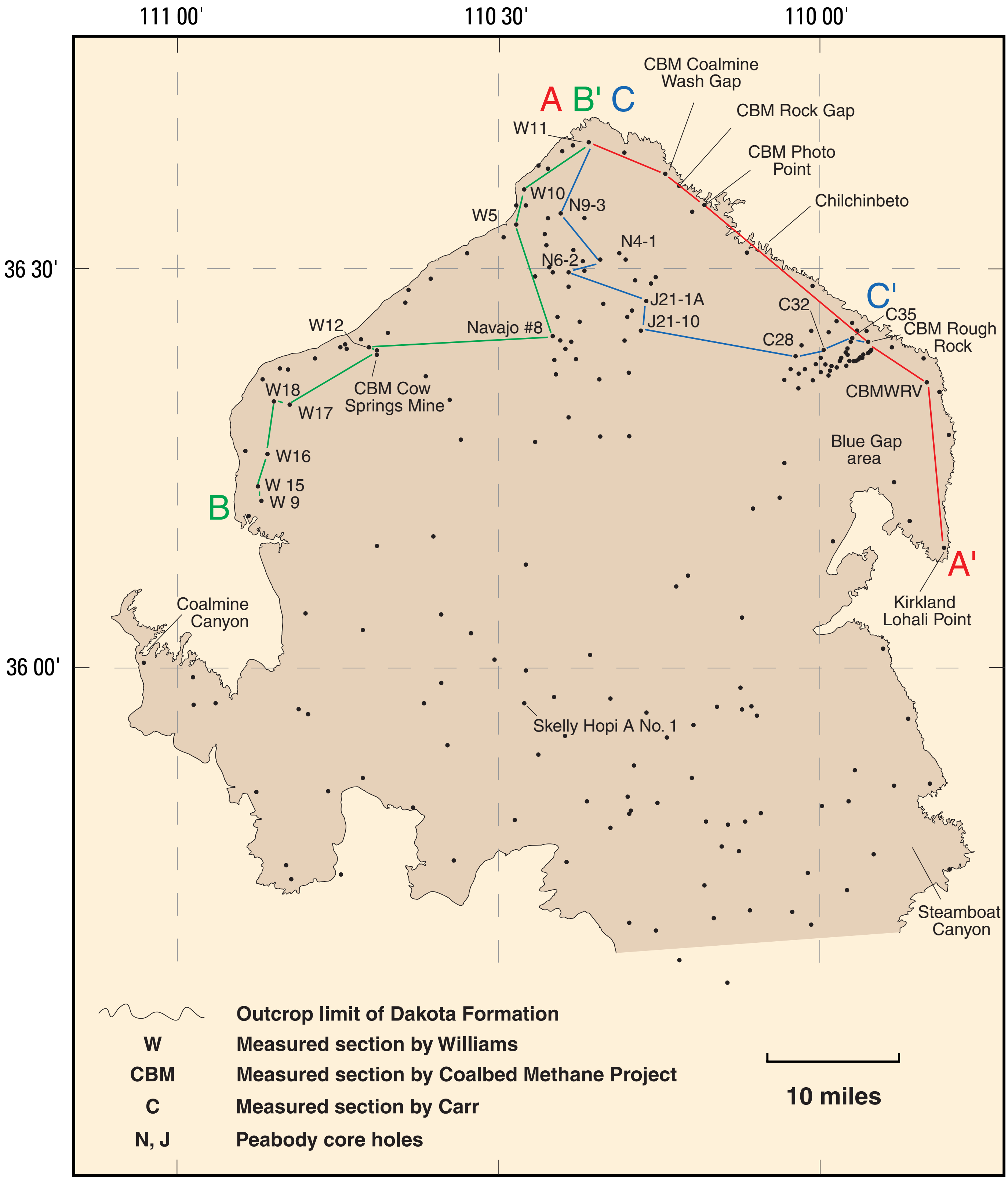

Figure 4. Locations of measured sections in Black Mesa Arizona from Carr (1987), Williams (1951), and the Coalbed Methane Project, and subsurface information including oil and gas, coal, and water well drill holes. Line of cross sections A-A′, B-B′, and C-C′ also shown. Locations cited in text or included in cross sections are labeled.

east, the Monument uplift to the north, and the Mogollon slope to the south (fig. 6). The Black Mesa Basin is a Laramide structure that has a depositional and tectonic history similar to that of the San Juan Basin in northwestern New Mexico and the Kaiparowits Basin in southern Utah (fig. 3). The basin is asymmetrical with steep dip on the eastern flank and gentler dip on the western margin, and it is crossed by numerous small-scale folds (fig. 7).

Along its north and east sides, Black Mesa is defined by prominent escarpments that result from erosion of cliff-forming strata, including the Late Jurassic Morrison Formation and Cow Springs Sandstone. It is capped by resistant sandstone strata of the Late Cretaceous Yale Point, Wepo, and Toreva Formations (fig. 8). Black Mesa is roughly circular, approximately 65 mi in diameter, and covers an area of 3,300 mi^2. Elevations range from about 6,000 ft above sea level in the southwestern part to 8,000 ft above sea level along the northeastern escarpment. It is a dissected mesa that rises as much as 2,000 ft above the surrounding terrain along its eastern margin, and slopes gently to the southwest, where the cliffs are 200–300 ft high. The top of the mesa slopes gently to the southwest, tending to expose younger strata in higher areas to the north and northeast and gradually older strata to the southwest (fig. 8).

Previous Mining Activity

Based on evidence from coal ash in kivas, primitive stone stoves, and pottery firing pits that date back at least to the year 1300 A.D., Black Mesa coal was first used by prehistoric peoples (Brew and Hack, 1939). Prior to 1926, small amounts of coal were mined to supply local fuel requirements. During 1926–34, 1942, and 1944–46, recorded coal production was 88,730 short tons valued at $358,800 (Wilson and Roseveare, 1949). From 1943 to 1960, less than 10,000 short tons was produced annually, most of which was mined for local use

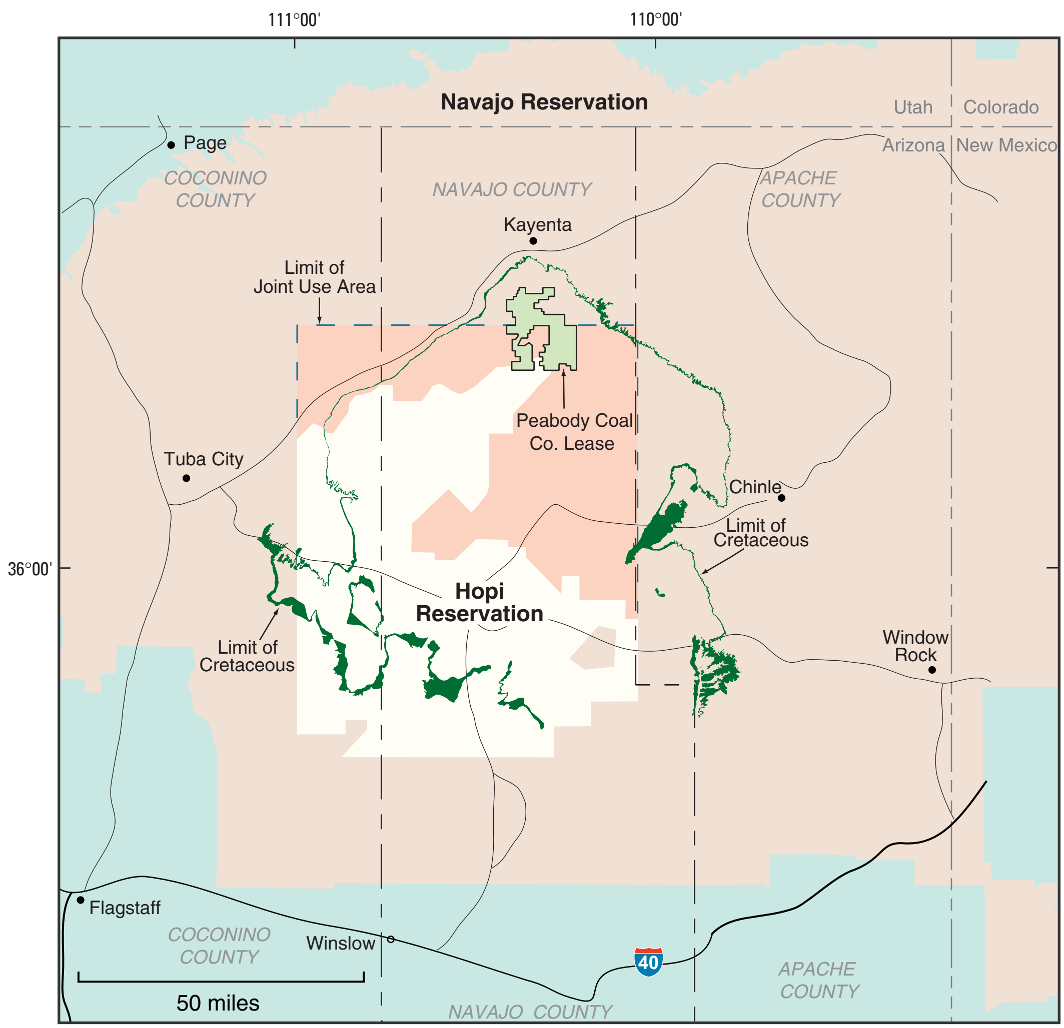

Figure 5. Area of study, Black Mesa Basin, northeastern Arizona. The dark-green irregular outcrop pattern of the Dakota Formation marks the limit of Cretaceous rocks.

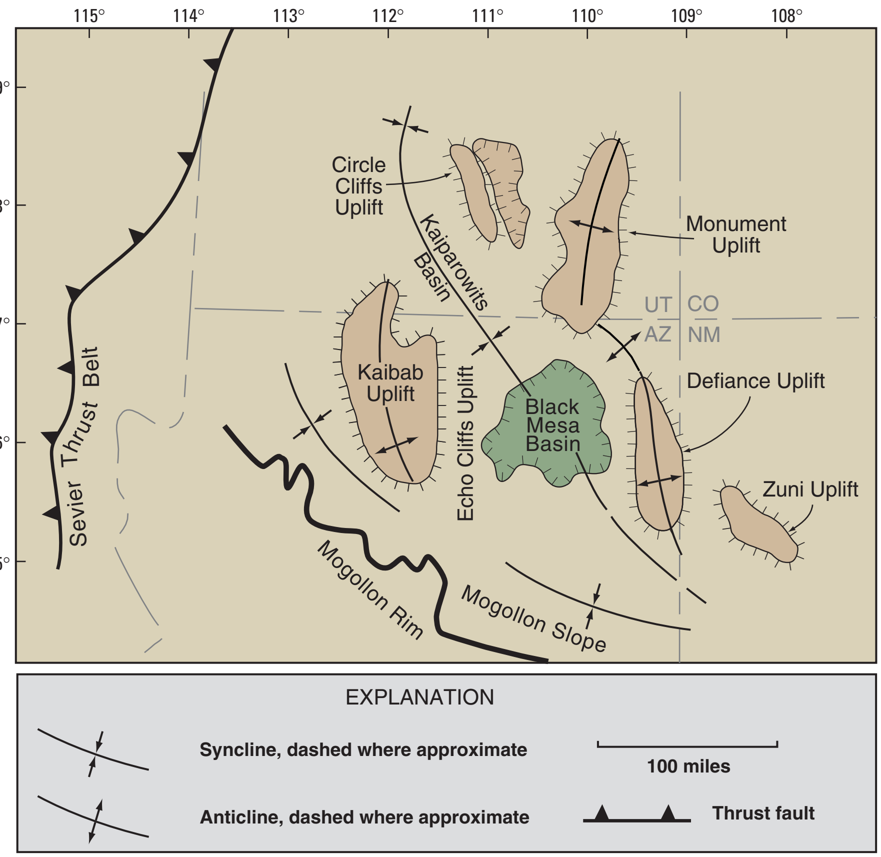

Figure 6. Large-scale Laramide folds in Cretaceous rocks of northeastern Arizona (modified from Kelley, 1958; Chapin and Cather, 1981; Nations and others, 1985; Davis and Kiven, 1975).

at schools on the reservations and for limited shipment to Holbrook, Winslow, and Flagstaff (Averitt and O'Sullivan, 1969). After natural gas pipelines were extended through northern Arizona about 1960, coal production decreased to less than 1,000 short tons annually (U.S. Bureau of Mines, 1960–67) until the Peabody Group mines began production.

The Black Mesa and Kayenta coal mines, operated by the Peabody Group, are located on Black Mesa near Kayenta and produce coal from a large reserve leased from the Navajo Nation and the Hopi Tribe (fig. 5). Royalties and other payments generated from the mining operations provide annual revenues for tribal operations. In addition, over 700 tribal members work at the Arizona mines and support facilities, placing Peabody among the Nation's largest private employers of American Indians. Peabody is the world's largest coal producer (Phillips and others, 1997).

Since 1975, coal production from the Black Mesa and Kayenta mines has averaged about 12 million short tons per year (Haven, 1997) (fig. 9). In 1996, coal production was 13,192,000 short tons, having an estimated value of $300 million.

High-quality coal is strip-mined from the Kayenta and Black Mesa mines. The coal is subbituminous with an average quality of 11,000 Btu/lb, 0.5 percent sulfur, and 10 percent ash. Both mines are now using both 150-ton- and 230-ton-capacity tractor trailer bottom-dump trucks to transport coal from the mine to the conveyors and pipeline feed plants.

The Black Mesa mine (fig.10) was opened in 1970 and produces approximately 4.5 million short tons of steam coal annually using draglines in two mining areas. The mine employs about 265 people and sells coal under terms of a 35-year contract signed in 1970. The coal is crushed, mixed with water, and then transported through the underground Black Mesa pipeline 273 mi to Southern California Edison's Mohave Generating Station near Laughlin, Nevada.

The Kayenta mine (fig. 10) is adjacent to the Black Mesa mine and began operating in 1973. This mine produces approximately 7.5 million short tons of steam coal annually using three draglines in three mining areas. The mine employs more than 400 people and sells coal under a 35-year contract with the Salt River Project. The coal is crushed, then carried by conveyor belt 17 mi to storage silos, where it is loaded on an electric train and transported 83 mi to the Navajo Generating Station near Page, Arizona.

Peabody's operations at Black Mesa are model reclamation programs. Mining and reclamation proceed at the same rate of approximately 500 acres annually. As an area is mined,

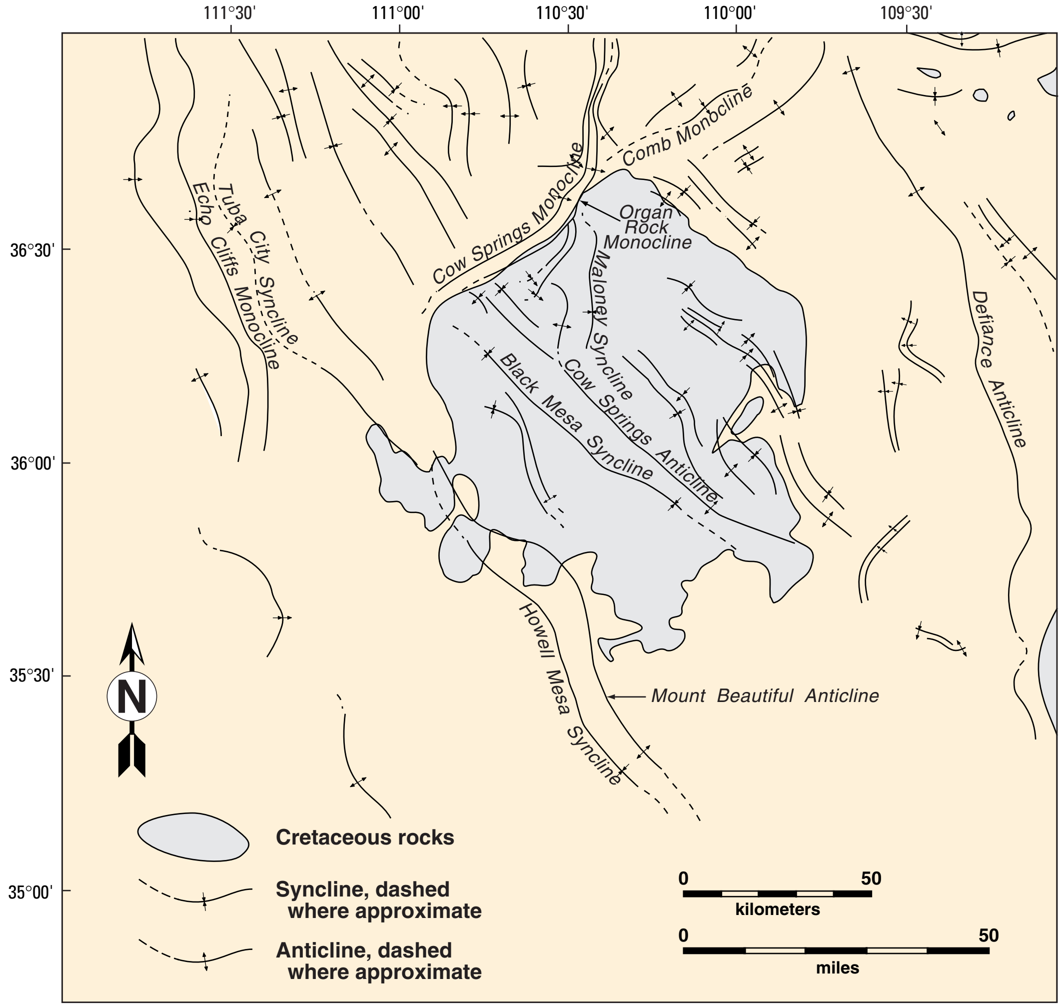

Figure 7. Laramide folds and erosional limits of Cretaceous rocks, northeastern Arizona (modified from Kelly, 1958; Davis and Kiven, 1975; and Reynolds, 1988).

the topsoil is removed and stored. After mining is completed, the topsoil is returned and the surface is contoured (figs. 11 and 29). The resultant reclaimed land, used for grazing, is more productive than the original land (Phillips and others, 1997).

Cretaceous Stratigraphy

Previous Geologic Studies

The first published reference to Cretaceous rocks of Black Mesa Basin was made by Newberry (1861). Campbell and Gregory (1911) recognized the Dakota Sandstone, the Mancos Shale, and the Mesaverde Formation in the Black Mesa area. Reeside and Baker (1929) correlated the Mesaverde Formation of Black Mesa Basin into southern Utah and they also recognized the Dakota Sandstone south of the Navajo Reservation in the Show Low area (fig. 3).

Williams (1951) described the Mancos Shale and raised the rank of the Mesaverde Formation to Group. The stratigraphy of the eastern part of Black Mesa was described by Merrin (1954). Repenning and Page (1956) recognized three formations within the Mesaverde Group, which they named, in ascending order, the Toreva Formation, the Wepo Formation, and the Yale Point Sandstone (fig. 12). These authors established the basic biostratigraphic framework of Cretaceous rocks in the area and correlated it with the faunal zones of the Cretaceous Western Interior. They further subdivided the Toreva Formation into three informal members. Young (1960) reviewed the stratigraphy of the Dakota Group of the Colorado Plateau, and Lessentine (1965) compared the Cretaceous stratigraphy and geologic history of the Kaiparowits Basin of Utah with that of the Black Mesa Basin. Peterson (1969) related the Cretaceous stratigraphic history in the Kaiparowits Basin to tectonic activity and interpreted the effect of local tectonic movement on sedimentation within the area. Peterson and Kirk (1977) established the chronologic similarity of major

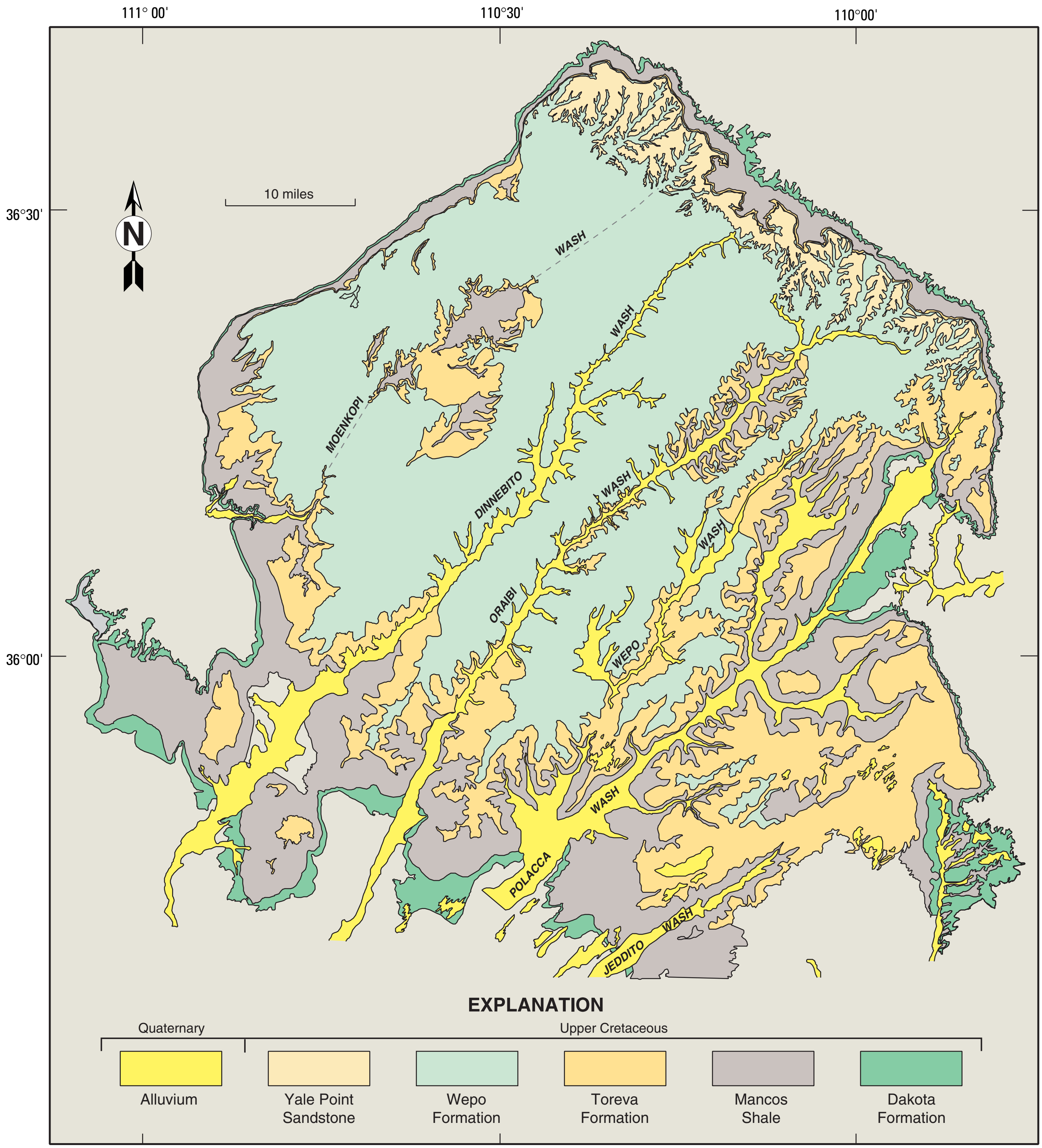

Figure 8. Geologic map of Black Mesa (modified from Cooley and others, 1969). See figure 12 for stratigraphic sequence.

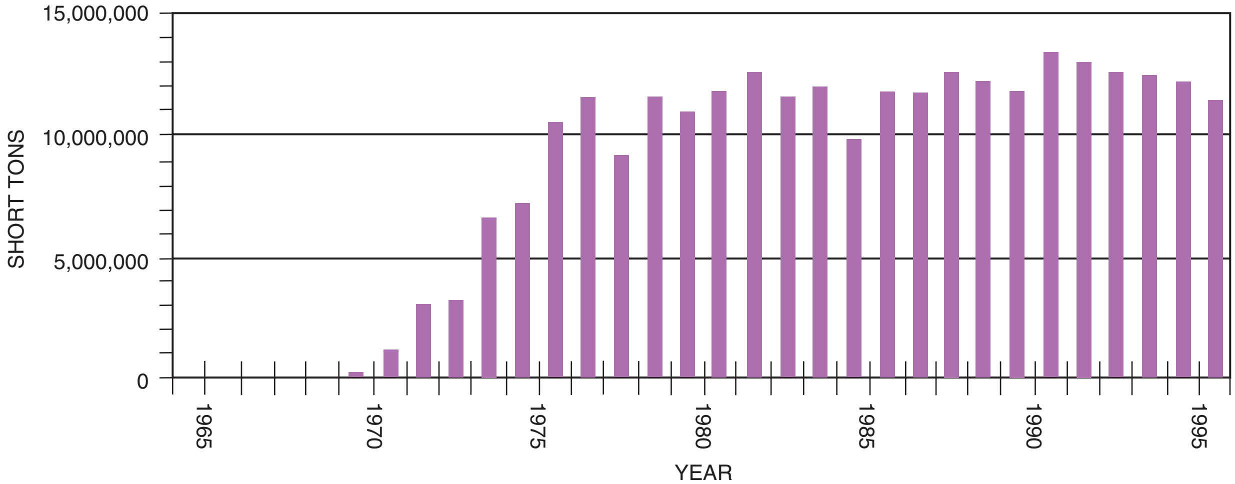

Figure 9. Annual coal production, Black Mesa Basin, Arizona (Navajo Nation Minerals Department, 1995).

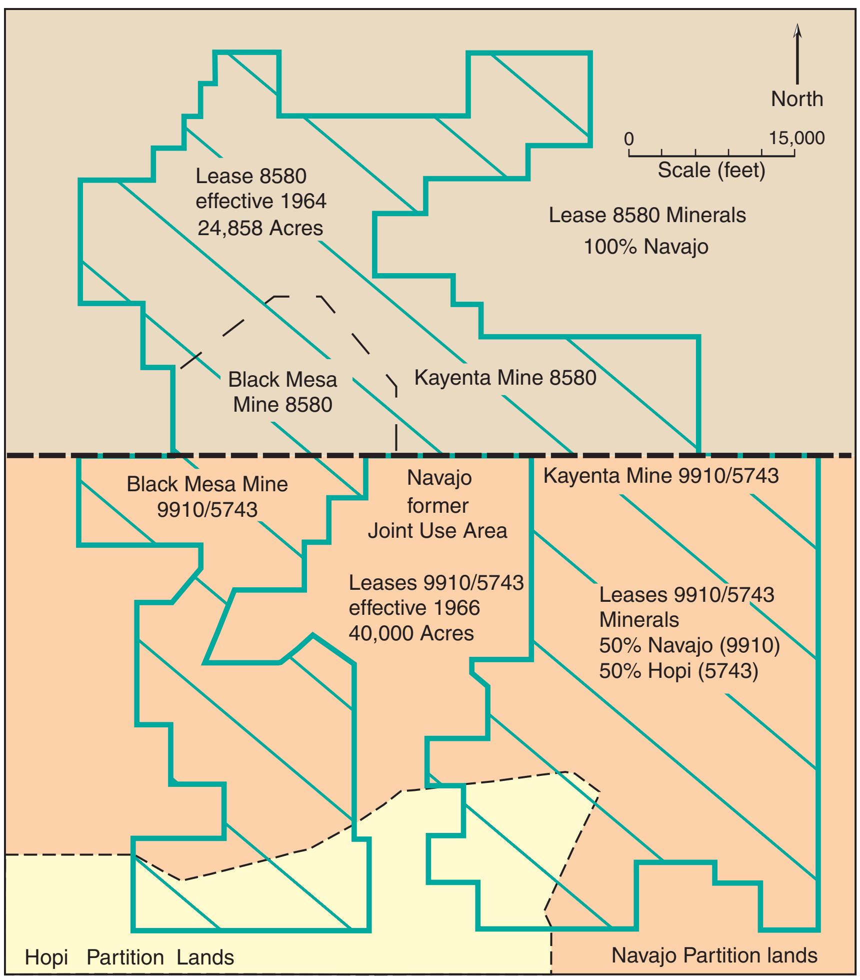

Figure 10. Peabody Group lease area and locations of Kayenta and Black Mesa mines (in green) (Haven, 1997; U.S. Office of Surface Mining., 1990). The Joint Use Area is shared equally between the Navajo Nation and the Hopi Tribe.

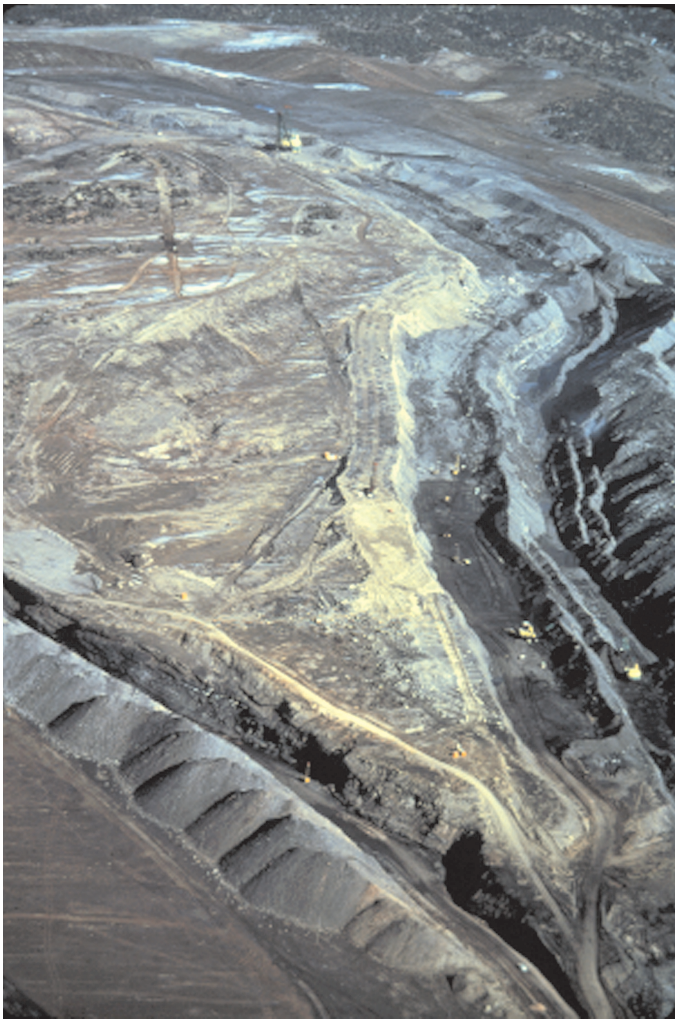

Figure 11. Black Mesa mine with active pit and backfilled pit.

depositional events between the Kaiparowits, Henry, San Juan, and Black Mesa basins. Franczyk (1983, 1987) revised the stratigraphic nomenclature of the Toreva Formation in northeastern Black Mesa by excluding the upper marine sandstone and shale of Repenning and Page (1956) and naming them the Rough Rock Sandstone and the Wind Rock Tongue of the Mancos Shale (fig. 13). Eaton and others (1987) revised the age assignment of the Rough Rock Sandstone and suggested that the name Mesaverde Group not be used for Cretaceous rocks in Black Mesa because they are considerably older than the type section of the Mesaverde Formation in southwestern Colorado.

Very little detailed information on the lithologic composition of the Mesaverde Group in Black Mesa has been published. Peirce and Wilt (1970) summarized the published information that was available at that time. Franczyk (1983, 1987) described the Toreva Formation, the lower carbonaceous member of the Wepo Formation, and the Rough Rock Sandstone in 10 measured sections along the southern half of the eastern escarpment. Carr (1987, 1991) described and correlated the upper carbonaceous member of the Wepo Formation in 41 measured sections in a small area along the Rough Rock road near the eastern edge of the mesa (fig. 4). Haven (1997) incorporated new lithologic descriptions, stratigraphic sections and maps of Cretaceous strata of Black Mesa that were prepared during this study (figs. 14 and 15). He also developed additional lithologic data and stratigraphic cross

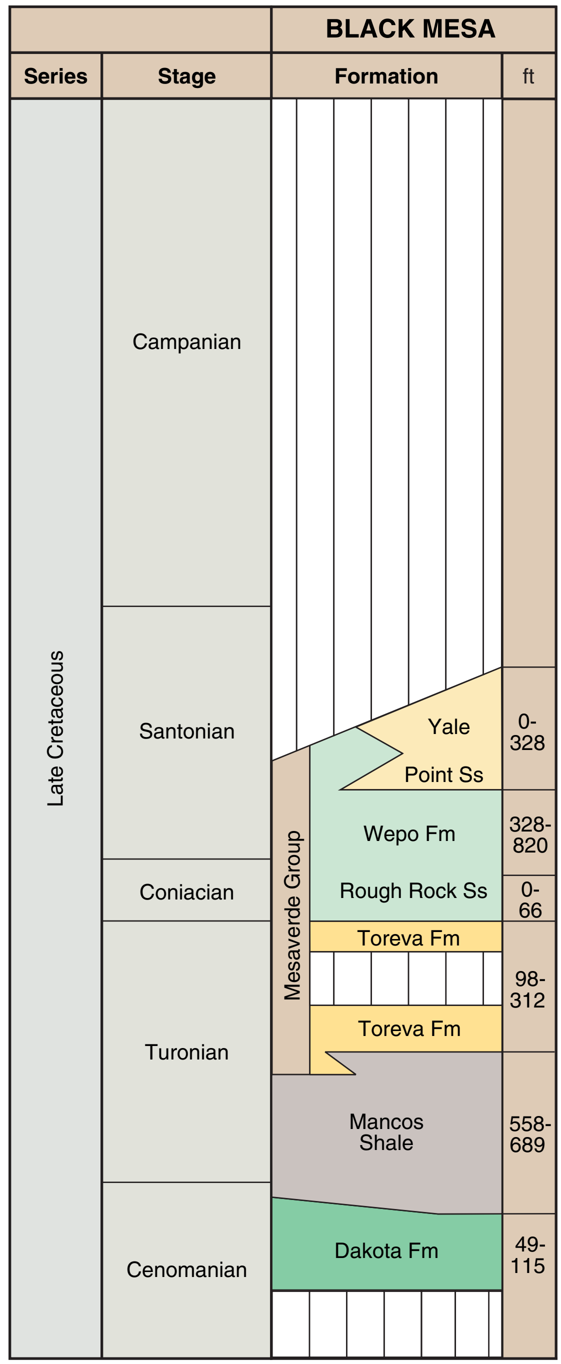

Figure 12. Stratigraphic sequence and ages of Upper Cretaceous formations in the Black Mesa Basin (modified from Eaton and others, 1987). White, vertically lined areas indicate hiatuses.

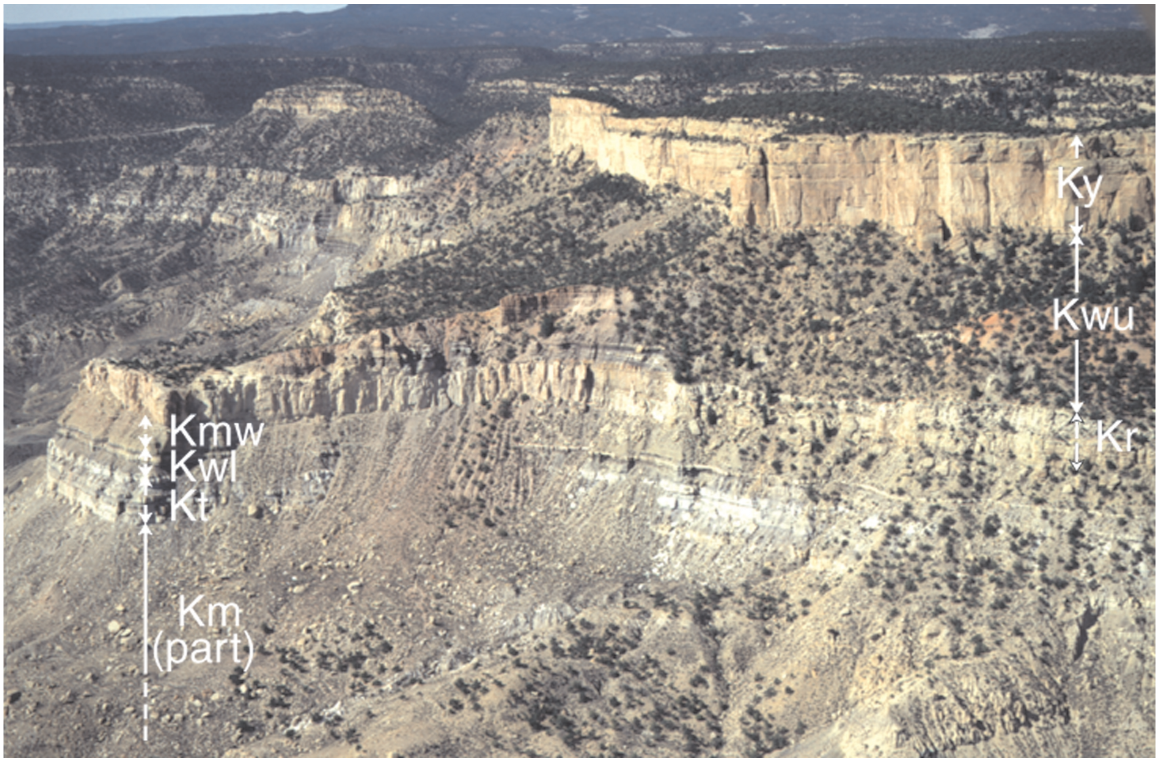

Figure 13. Oblique aerial photograph of the northeastern escarpment in the Rough Rock area of Black Mesa. Ky, Yale Point Sandstone; Kwu, upper carbonaceous member of the Wepo Formation; Kr, Rough Rock Sandstone; Kmw, Wind Rock Tongue of the Mancos Shale; Kwl, lower carbonaceous member of the Wepo Formation; Kt, Toreva Formation; Km, Mancos Shale; the Dakota Formation is out of view below the bottom of photo.

sections of the Wepo Formation and revised estimates of coal resources in the Wepo Formation.

Cretaceous rocks of Black Mesa were divided into the Dakota Sandstone, Mancos Shale, and Mesaverde Formation by Gregory (1917). Subsequently, several other authors have refined the interpretations of the stratigraphy, age, and depositional environments of these units, which are summarized below.

Dakota Formation

The Upper Cretaceous Dakota Formation unconformably overlies Jurassic strata throughout the Black Mesa region and northwestward into southern Utah. Although there is no apparent angular unconformity at any one exposure, the Dakota Formation unconformably overlies progressively older deposits toward the west and southwest (Williams, 1951). An erosional surface was cut into successively older rocks toward the Mogollon Highlands to the south and the Sevier orogenic belt to the west, and this resulted in a beveled surface on which the Dakota Formation was deposited. Along the north and northeast sides of Black Mesa, the Dakota Formation overlies the Upper Jurassic Cow Springs Member of the Entrada Sandstone and the Morrison Formation (Peterson, 1988). In southern Black Mesa, the Dakota rests on the middle part of the Entrada Sandstone (fig. 16). Near Show Low (fig. 3), about 70 mi south of the Black Mesa area, the Dakota overlies the Upper Triassic Chinle Formation, and farther south at McNary, Arizona, it rests on upper Paleozoic strata (Harshbarger and others, 1957).

The Dakota Formation is divided into three members; lower sandstone member, middle carbonaceous member, and upper sandstone member (fig. 16). Lithologic units within the Dakota are highly lenticular and thin and thicken laterally. The thickness of the Dakota Formation varies from 50 to 350 ft with no apparent trend to this thickening and thinning (fig. 17).

The lower sandstone member of the Dakota Formation in Arizona has yielded no age-diagnostic fossils, but is believed to be of Cenomanian age (Repenning and Page, 1956; Cobban and Hook, 1984). Palynological data from the middle carbonaceous member has been interpreted as indicating a Cenomanian age (Agasie, 1969; Carter, 1975; am Ende, 1986). The upper sandstone member is late Cenomanian in northern Arizona, based on bivalve and ammonite zonation (Cobban and Hook, 1984; Kirkland and Cobban, 1986).

The Dakota Formation in the Black Mesa area generally

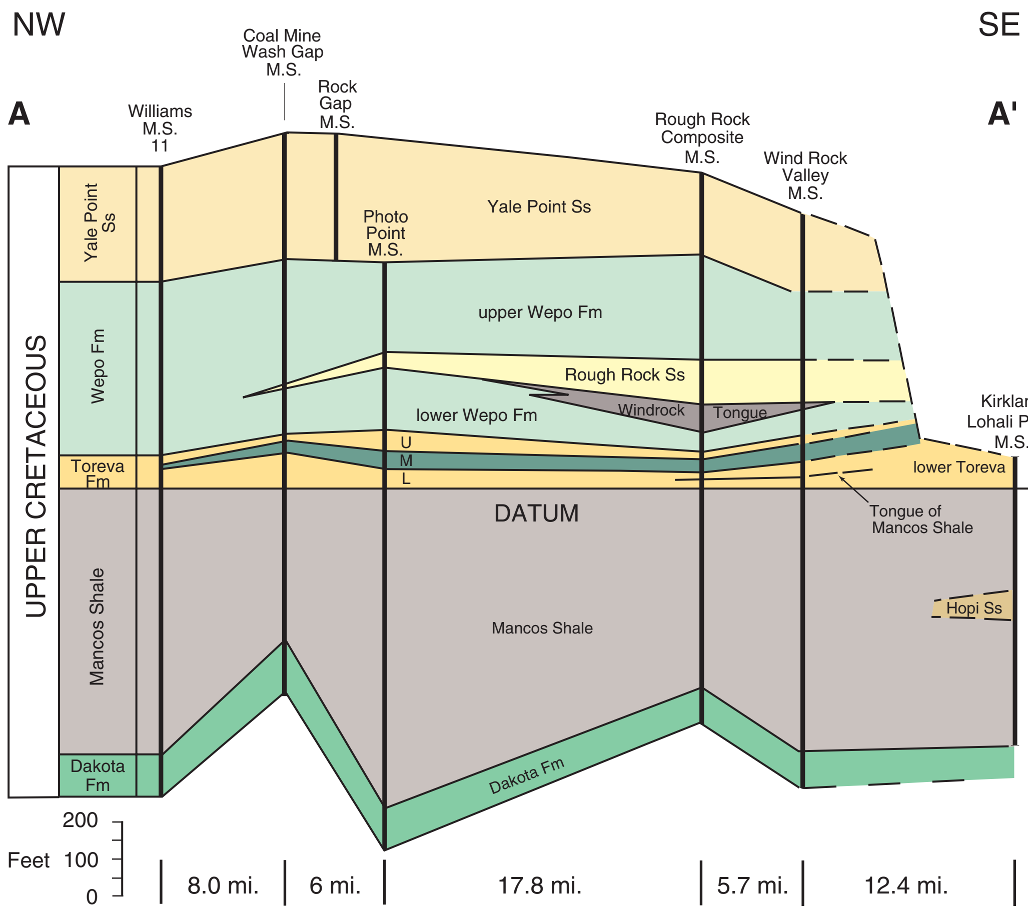

Figure 14. Diagrammatic NW.-SE. stratigraphic cross section A-A′ of Cretaceous rocks, Black Mesa Basin, Arizona. Location of cross section and measured sections (M.S.) are shown on figure 4.

grades upward through fluvial, paludal, brackish, and near-shore marine deposits, although considerable lateral variation occurs (Repenning and Page, 1956; Molenaar, 1983; Kirkland, 1983, 1991).

Mancos Shale

The Mancos Shale overlies the upper sandstone member of the Dakota Formation and is exposed in steep to gentle slopes around the periphery of Black Mesa, and in areas of deep erosion on top of the mesa, especially where regional drainages cross anticlinal axes (figs. 7 and 8). The Mancos Shale is predominantly dark gray, bluish-weathering, siltstone and claystone. It is about 700 ft thick on the north side of Black Mesa and thins to about 475 ft in the southernmost complete exposures at Blue Point on Padilla Mesa (Kirkland, 1983) (fig. 18). It continues to thin southward toward its pinch-out near Show Low (Repenning and Page, 1956).

The Mancos shale was divided by Kirkland (1983) into four informal members, which were later designated the: (1) lower fossiliferous calcareous shale member; (2) middle well-laminated calcareous shale member, (3) Hopi sandy member, and (4) upper noncalcareous claystone member (Eaton and others, 1987). Franczyk (1987) named the Wind Rock Tongue of the Mancos Shale that occurs in the lower part of the Wepo Formation (figs. 14 and 16).

The age of the Mancos Shale at Black Mesa is late Cenomanian to middle Turonian, based on ammonite biostratigraphic zonation (Cobban and Hook, 1984; Kirkland and Cobban, 1986). The lower Mancos fauna reflects the maximum transgression and depth of the Western Interior Seaway near the Cenomanian-Turonian boundary (Kauffman, 1977, 1984; Kirkland, 1983). However, Olesen (1987, 1991) demonstrated that maximum depth in the southern part of Black Mesa did not occur until early middle Turonian time (base of *Collignoniceras woolgari woolgari* zone), based on the occurrence of abundant planktonic forams in that part of the lower Mancos Shale.

The upper contact of the Mancos Shale is gradational and intertongues with the overlying Toreva Formation. The contact is placed where sandstone begins to dominate the sequence (Kirkland, 1983).

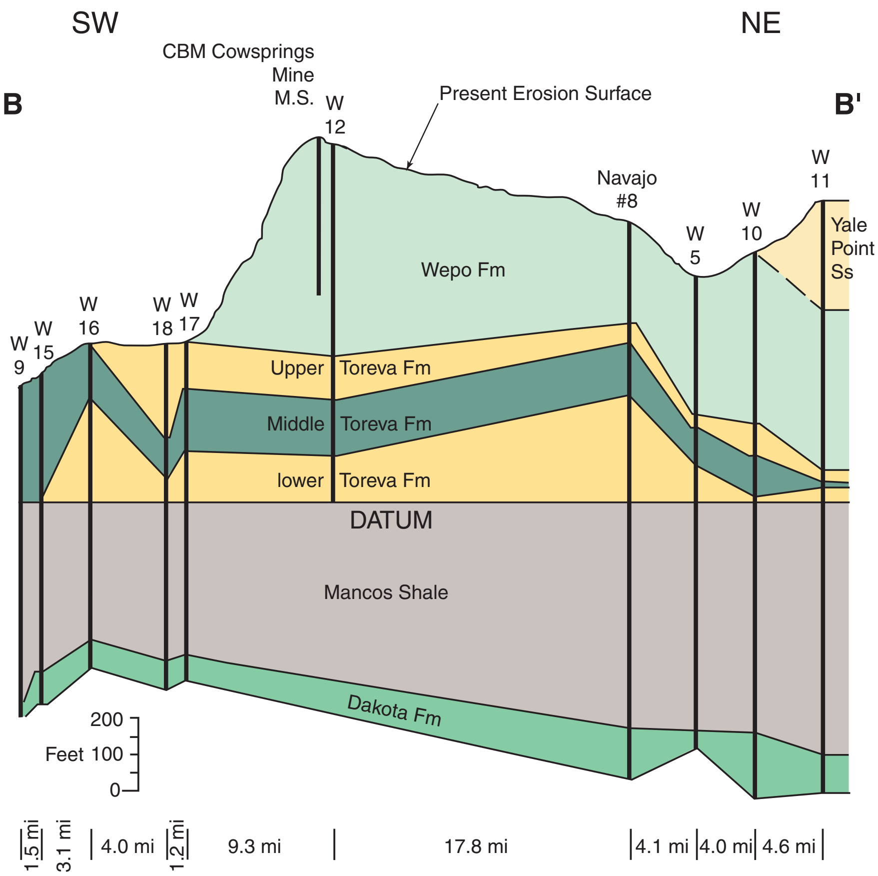

Figure 15. Diagrammatic SW.-NE. stratigraphic cross section B-B′ of Cretaceous rocks, Black Mesa Basin, Arizona. Location of cross section and measured sections (M.S.) are shown on figure 4.

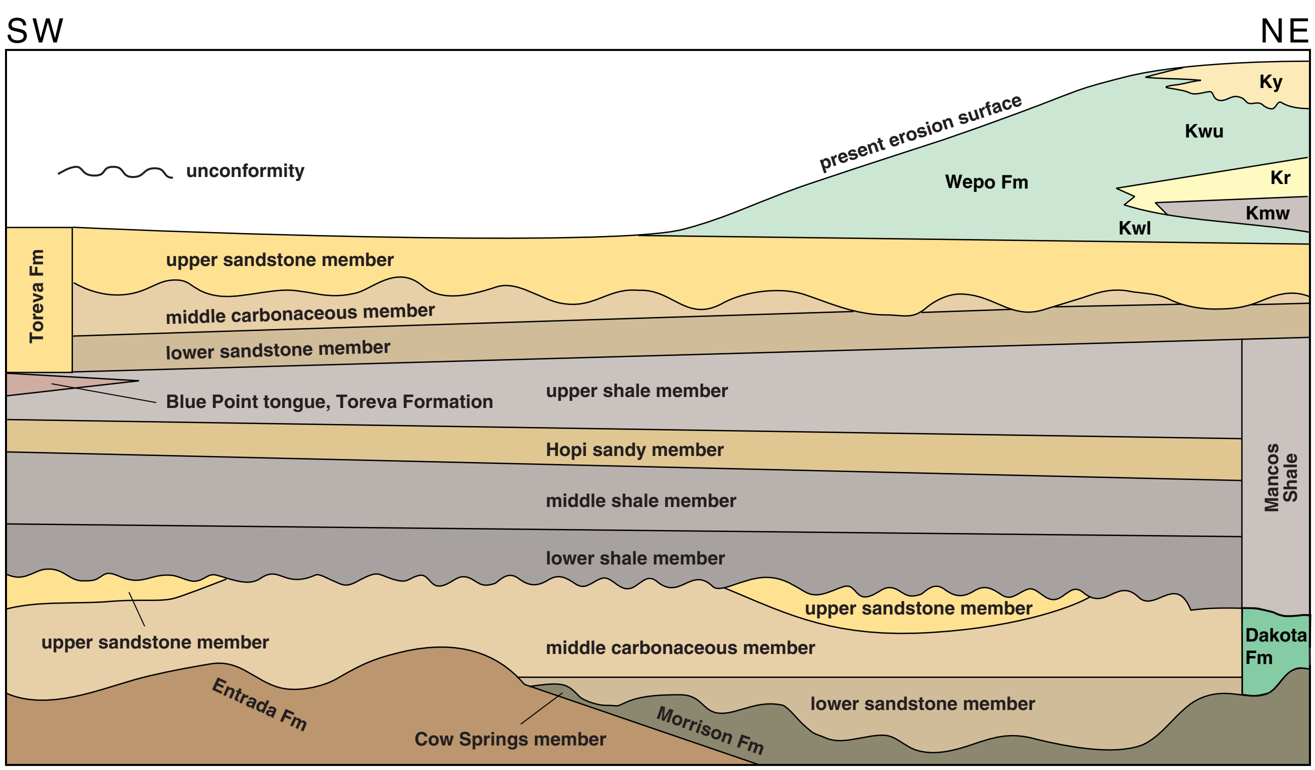

Figure 16. Generalized schematic diagram showing cross sectional distribution of Cretaceous units and the contact with the Jurassic Entrada and Morrison Formations from southwest to northeast across Black Mesa (modified from Eaton and others, 1987). Ky, Yale Point Sandstone; Kwu, upper carbonaceous member of the Wepo Formation; Kr, Rough Rock Sandstone; Kmw, Wind Rock Tongue of the Mancos Shale; and Kwl, lower carbonaceous member of the Wepo Formation.

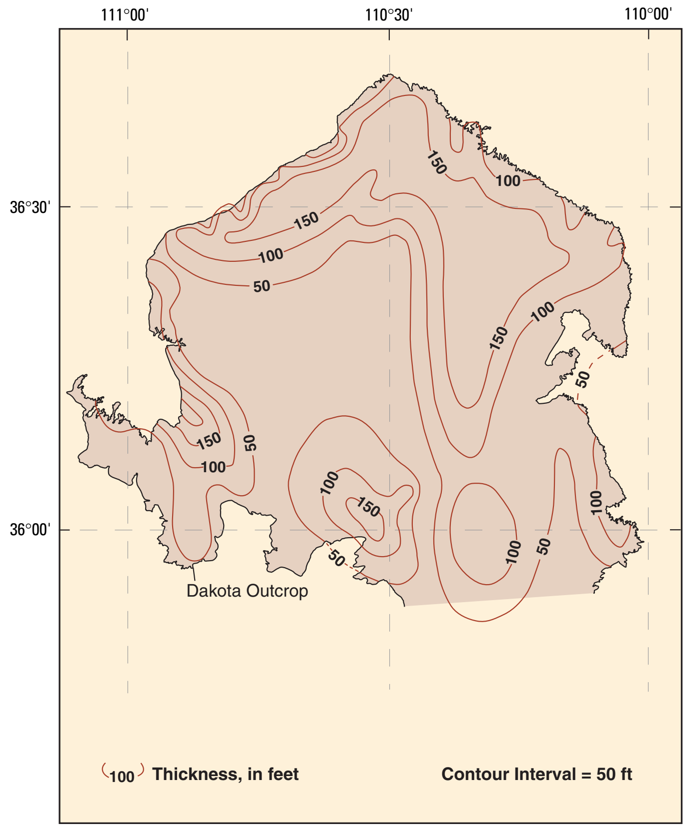

Figure 17. Isopach map of the Dakota Formation, Black Mesa Basin, Arizona.

Mesaverde Group

On Black Mesa, the term "Mesaverde Group" refers collectively to units that overlie the Mancos Shale. The three formations on Black Mesa as defined by Repenning and Page (1956) are, in ascending order, the Toreva Formation, the Wepo Formation, and the Yale Point Sandstone (figs. 14 and 15). These formations were deposited in a variety of environments along coastal plains and strandlines that record the last influence of marine environments in northern Arizona (Molenaar, 1983).

Toreva Formation

The Toreva Formation in the southern part of Black Mesa was subdivided into three members by Repenning and Page (1956): a lower sandstone member, a middle carbonaceous member, and an upper sandstone member (fig. 16). The Toreva Formation crops out over an area of about 743 mi^2 and varies from about 200 to 470 ft in thickness (figs. 8 and 19).

The lower sandstone member is about 100 ft thick and forms a prominent cliff throughout Black Mesa. It is composed of fine- to medium-grained, quartzose sandstone with cross-bedding that is indicative of offshore to beach depositional environments and is gradational with the underlying Mancos Shale (Repenning and Page, 1956).

The middle carbonaceous member consists of carbonaceous siltstones, mudstones, and sandstones that are exposed around the perimeter and at the surface in the southern half of Black Mesa but is absent from the northern part (Peirce and Wilt, 1970). It forms a slope approximately 100 ft high in southern Black Mesa and thins rapidly to the north apparently from erosion of its upper surface. It is composed of lenticular shale, coal, and sandstone, reflecting delta-plain deposition (Franczyk, 1983, 1987). The flat and thinly bedded dark mudstones, varicolored siltstones, coal, and thin yellowish-gray sandstones of the middle carbonaceous member were probably deposited in marshy lagoons and swampy areas behind the beach as the sea retreated farther eastward.

The upper sandstone member consists dominantly of medium- to coarse-grained, sheetlike sandstone bodies that grade upward into tabular and lenticular sandstones and fine-grained deposits. It is commonly conglomeratic, and sedimentary structures indicate deposition by streams flowing northeastward across a broad coastal plain. The upper sandstone member generally rests on a sharp scour contact with the middle carbonaceous member, but locally rests directly on the lower sandstone member (Peirce and Wilt, 1970). It varies

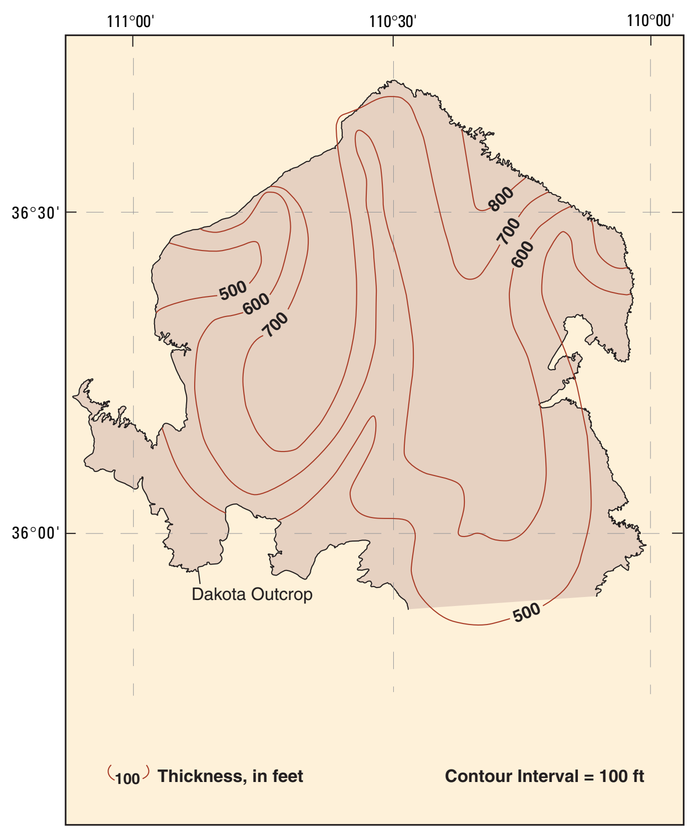

Figure 18. Isopach map of the Mancos Shale, Black Mesa Basin, Arizona.

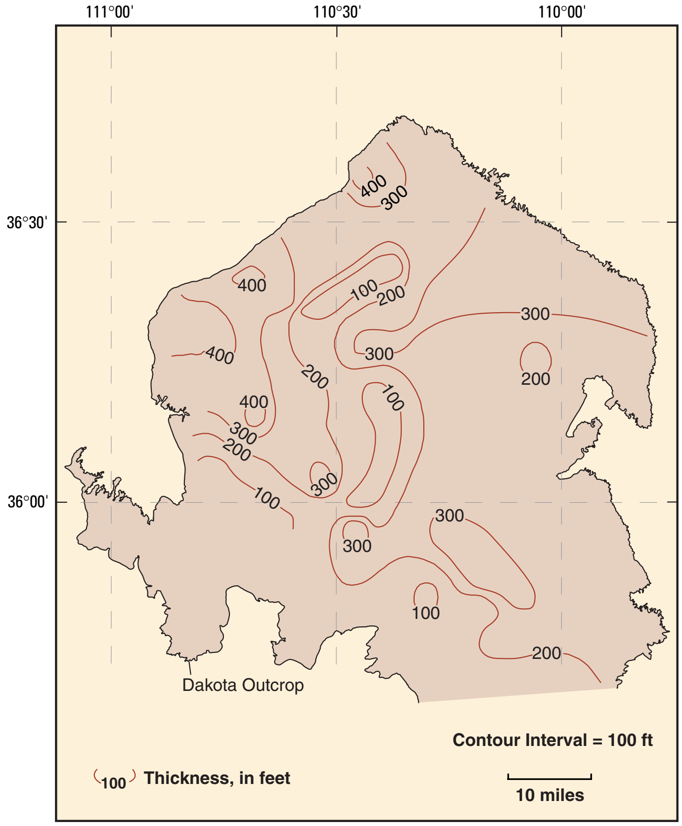

Figure 19. Isopach map of the Toreva Formation, Black Mesa Basin, Arizona.

from 25 to 120 ft in thickness and forms a prominent cliff. The upper sandstone member was deposited in a continental fluvial environment (Franczyk, 1983, 1987) and overlies an erosional unconformity that represents a late Turonian diastem (Peterson and Kirk, 1977; Eaton and others, 1987).

The Toreva Formation in northern Black Mesa was redefined by Franczyk (1983, 1987) to exclude three lithologic units from the Toreva as described by Repenning and Page (1956). Franczyk (1983, 1987) renamed these units, respectively, the lower carbonaceous member of the Wepo Formation, the Wind Rock Tongue of the Mancos Shale, and the Rough Rock Sandstone (figs. 12 and 16).

Wepo Formation

The Wepo Formation is exposed at the surface across much of Black Mesa but has been eroded from the southern and western margins (figs. 8 and 20). Along the northeastern margin, it is capped by the massive, yellowish-gray Yale Point Sandstone (figs. 8, 14, and 15). About 1,270 mi^2 of the Wepo Formation is exposed at the surface of Black Mesa (Peirce and Wilt, 1970).

The Wepo Formation varies in thickness from 400 ft in the southwestern portions of Black Mesa to 200 ft in the northeastern portions (fig. 20). Thinning of the Wepo to the northeast is due to intertonguing with the underlying Toreva Formation and the overlying Yale Point Sandstone (Molenaar, 1983) (figs. 15 and 16). It is 600 ft thick east of Cow Springs, more than 400 ft thick in the central part of its exposure, and to the east it thins to 318 ft at Rough Rock (fig. 20). Because the top of Black Mesa is an erosional surface, the remaining Wepo thickness in a particular area depends upon its structural position and the extent of downcutting by streams (Peirce and Wilt, 1970).

The Wepo Formation is composed dominantly of interbedded shale, siltstone, sandstone, and coal that erode to form steep slopes. Locally interbedded lenticular, trough-crossbedded, well-cemented sandstones form cliffs as much as 40 ft high. The flat-lying shales, siltstones, and coal commonly contain a well-preserved flora, and a brackish-water fauna is preserved in some of the shales. Siderite concretions and gypsum are common through much of the formation.

The Wepo Formation is undifferentiated throughout most of its extent, but was subdivided along the northeastern margin of Black Mesa into the lower and upper carbonaceous members where they are separated by the Wind Rock Tongue of the Mancos Shale and the Rough Rock Sandstone (Franczyk, 1983, 1987) (figs. 14 and 16). The Rough Rock Sandstone contains sedimentary structures and trace fossils that indicate

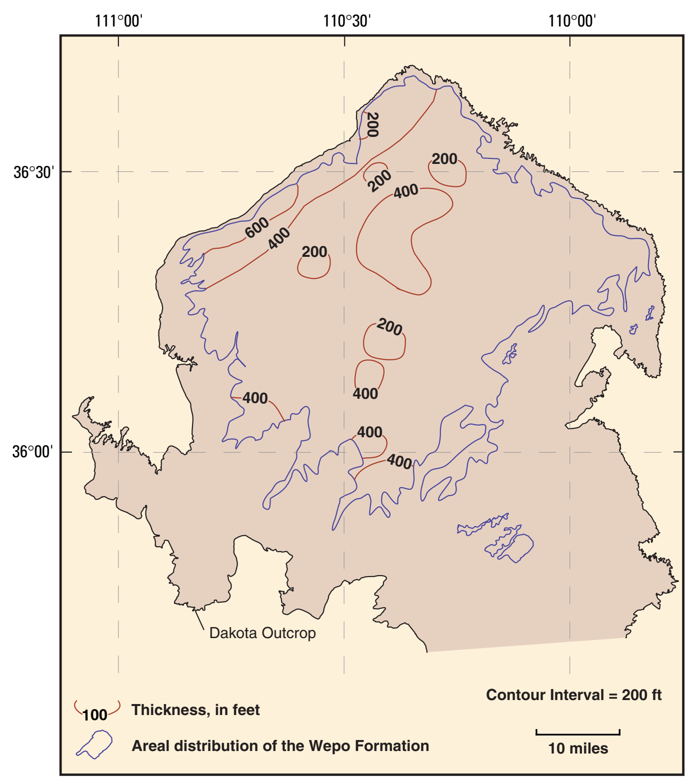

Figure 20. Isopach map of the Wepo Formation, Black Mesa Basin, Arizona.

a regressive beach deposit (Molenaar, 1983) and inoceramids that indicate a Coniacian age (fig. 12) (Eaton and others, 1987). Both members of the Wepo Formation consist of coal, carbonaceous siltstone, and mudstone, and tabular and lenticular sandstone bodies with scour bases. The lower carbonaceous member is gradational with the upper sandstone member of the Toreva Formation, and its upper contact with the Wind Rock Tongue or the Rough Rock Sandstone is erosional. Carr (1987, 1991) measured and described 41 sections of the upper carbonaceous member of the Wepo Formation in the Rough Rock area and interpreted the environment of deposition as a delta plain (figs. 4 and 21).

Yale Point Sandstone

The Yale Point Sandstone is present only along the northeastern edge of Black Mesa, where it forms a prominent pale-orange cliff approximately 200 ft high, and extends about 6 mi west of the escarpment. (figs. 8, 15, 16, 21, and 22). The limited lateral extent is a result of intertonguing with the Wepo Formation and extensive beveling of Black Mesa to the south and west by Cenozoic erosion (Repenning and Page, 1956). The thick sandstone deposits of the Yale Point Sandstone represent stacked beach and nearshore marine sands, shoreward (to the west) of which, thick coal deposits of the Wepo Formation accumulated on a delta plain. No Cretaceous rocks younger than the Santonian Yale Point Sandstone are present in northeastern Arizona (fig. 12). Cenozoic erosion may have removed as much as 4,500 ft of Cretaceous rocks from the Black Mesa, based on the thickness of younger Cretaceous rocks in the San Juan Basin (Molenaar, 1983; Nations, 1989; Cook and Bally, 1975). This depth of burial would have caused a higher degree of thermal maturation and methane gas generation than might be expected for the relatively shallow present-day burial depths of the coals in Black Mesa.

Geophysical Type Log

Even though there are only a few deep drill holes in Black Mesa, they provide excellent subsurface information. We have selected one of these (fig. 4), the Skelly Hopi A No.1 well, as the geophysical type log for the area, from which to pick the contacts of the Wepo, Toreva, Mancos, and Dakota Formations. The log was used to differentiate the sand and shale intervals using the gamma-ray and neutron curves (fig. 23).

Distribution of Coal in Black Mesa Basin

Coal seams occur in the carbonaceous members of the Dakota, Toreva, and Wepo formations. The Yale Point Sandstone contains only a minor seam or two in one small area and is therefore not considered to be of economic interest (Peirce and Wilt, 1970). The areas of outcrop of various formations are shown on the geologic map of Black Mesa (fig. 8).

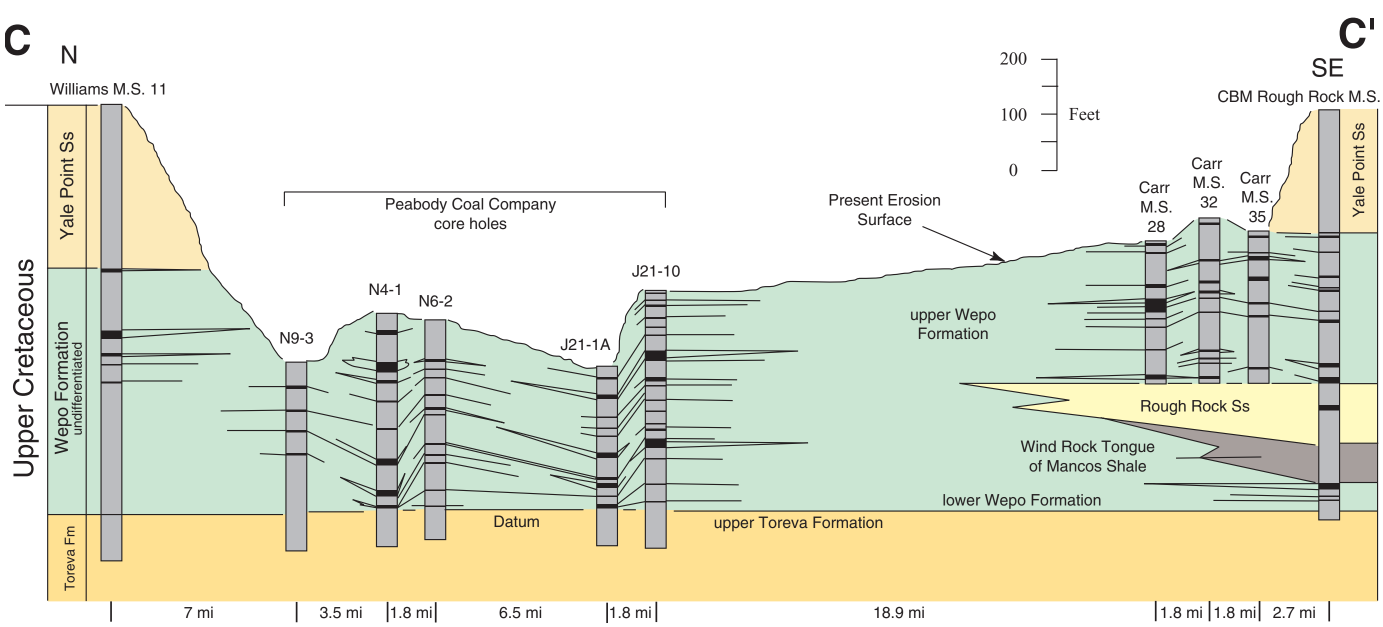

Figure 21. N.-SE. stratigraphic cross section C-C′ of the Wepo Formation (modified from Haven, 1997). Measured sections (M.S.) are from Williams (1951), Carr (1987), and the Coalbed Methane Project. Location of cross section shown on figure 2.

Figure 22. Henry Haven measuring and describing a section of the Yale Point Sandstone.

These formations were deposited in a variety of coal-forming environments along coastal plains and strandlines that record the last influence of marine environments in northern Arizona (Molenaar, 1983). Coal thickness in the Black Mesa Basin is interpreted from isopach maps of the cumulative coal thickness for all formations (fig. 24), coal thickness in the Dakota Formation (fig. 25), coal thickness in the Toreva Formation (fig. 26), and coal thickness in the Wepo Formation (fig. 27). The black outline of each of these maps indicates the erosional limit of the Dakota Formation.

Coal Distribution and Thickness in the Dakota Formation

The middle carbonaceous member of the Dakota Formation contains yellowish-gray to black carbonaceous siltstone, shale, coal, and thin sandstones. The unit weathers into a smooth slope with minor ledges, varies irregularly in thickness between 20 and 80 ft, and is thickest on the eastern side of Black Mesa where the other Dakota members are absent (Pickens, 1974). The better quality coal seams are in the upper siltstone-claystone beds of the middle member near the upper sandstone member. Most seams average 2 ft in thickness except in the southeastern and southwestern portions of the mesa (fig. 25) where they are 7–9 ft thick, (Kiersch, 1955;

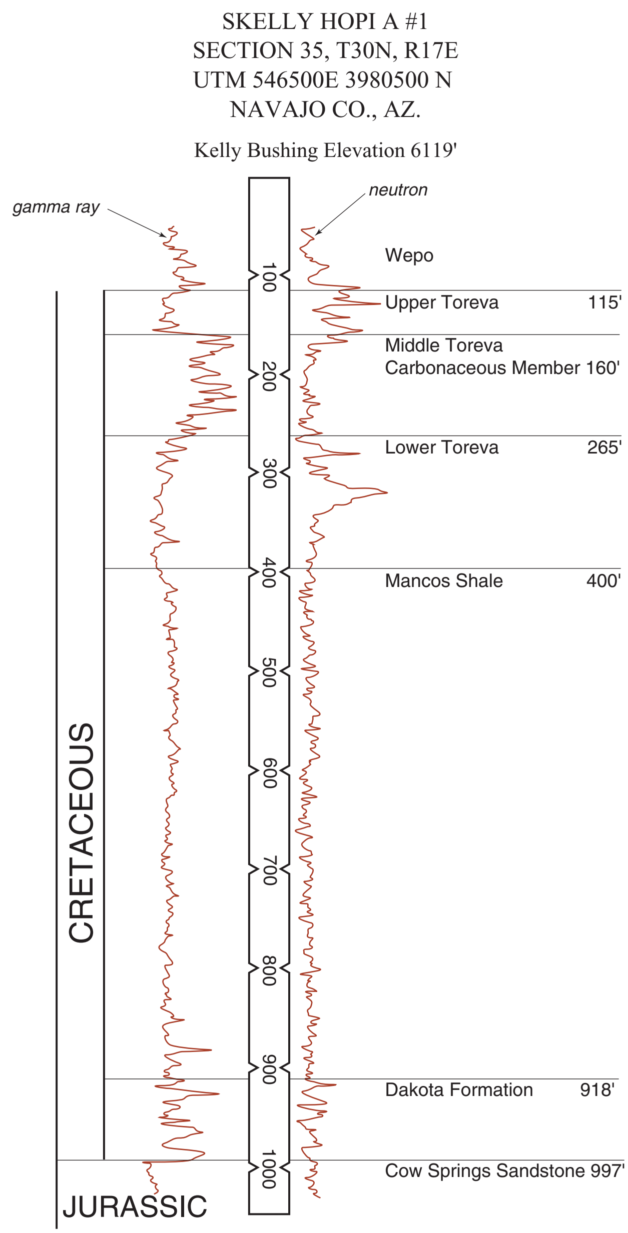

Figure 23. Typical Black Mesa subsurface log, Skelly Hopi A No. 1 (from Haven, 1997). Location shown on figure 4. The gamma-ray curve counts increase to the right indicating shaley intervals, whereas a cleaner sandstone yields a lower count and the curve is deflected to left. The neutron curve is deflected to the right in sandy intervals and to the left in shaley intervals.

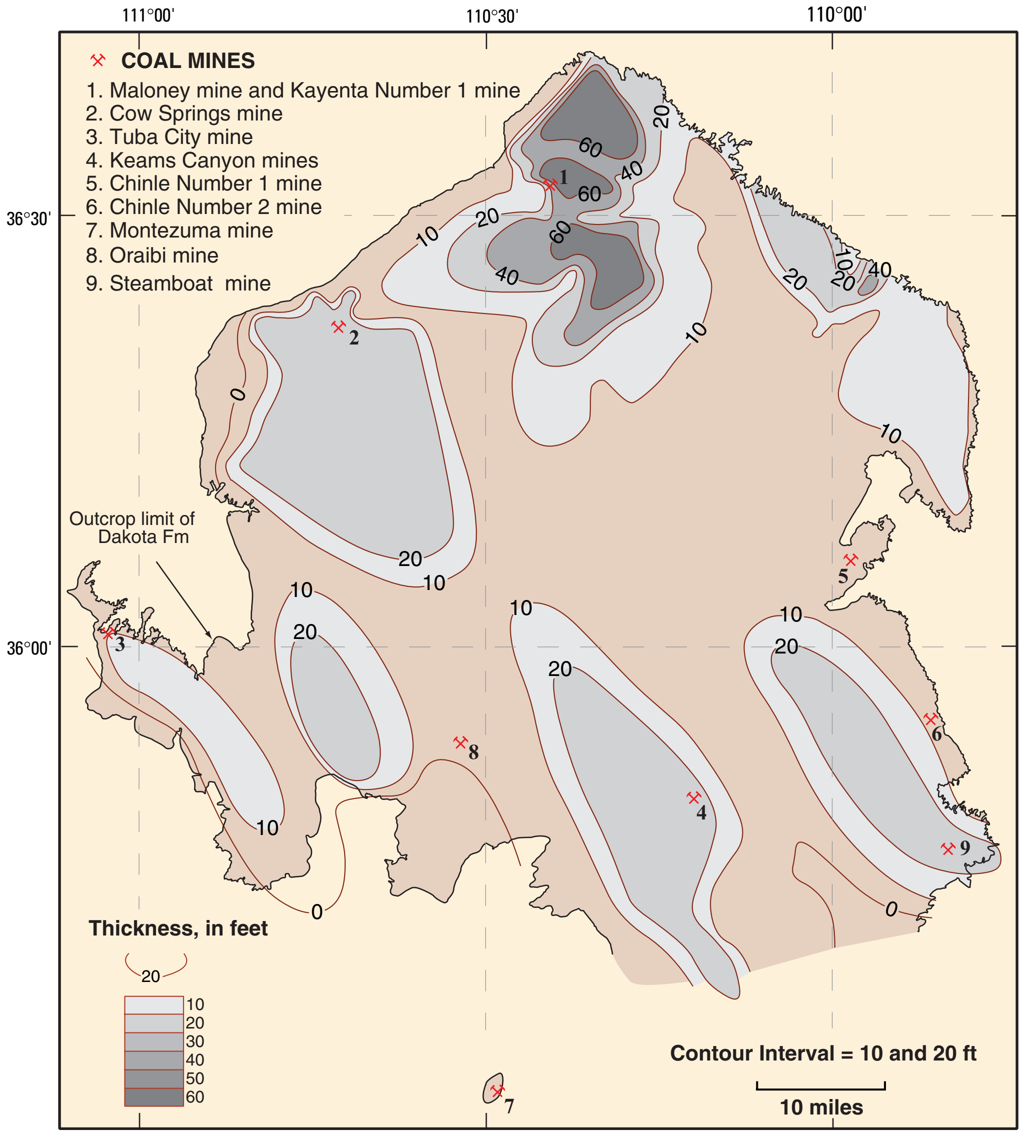

Figure 24. Cumulative net-coal thickness in Dakota, Toreva, and Wepo Formations, Black Mesa, Arizona. Historic coal mines are shown. See figure 27 for area of active mining.

Williams, 1951; Merrin, 1954). Some coal seams are lenticular and vary in thickness from several feet to several inches within a few hundred feet laterally as a result of deposition within local depressions or by being cut off by other channels (Williams, 1951; Kiersch, 1955). Although the carbonaceous member occurs nearly everywhere in Black Mesa, the thicker and more extensive coal deposits are in the southwestern part where the upper sandstone member is frequently absent. Three mines have obtained coal from this formation, the Tuba City No. 3 mine, the Chinle No. 1 mine, and the Montezuma mine (figs. 25 and 28).

Coal occurrence and (or) thickness has been determined from 92 measured sections and other data points, and its thickness in the basin may be interpreted from the coal isopach map (fig. 25).

Coal Distribution and Thickness in the Toreva Formation

Coal beds or carbonaceous siltstones occur in the Toreva Formation in all measured sections throughout Black Mesa,

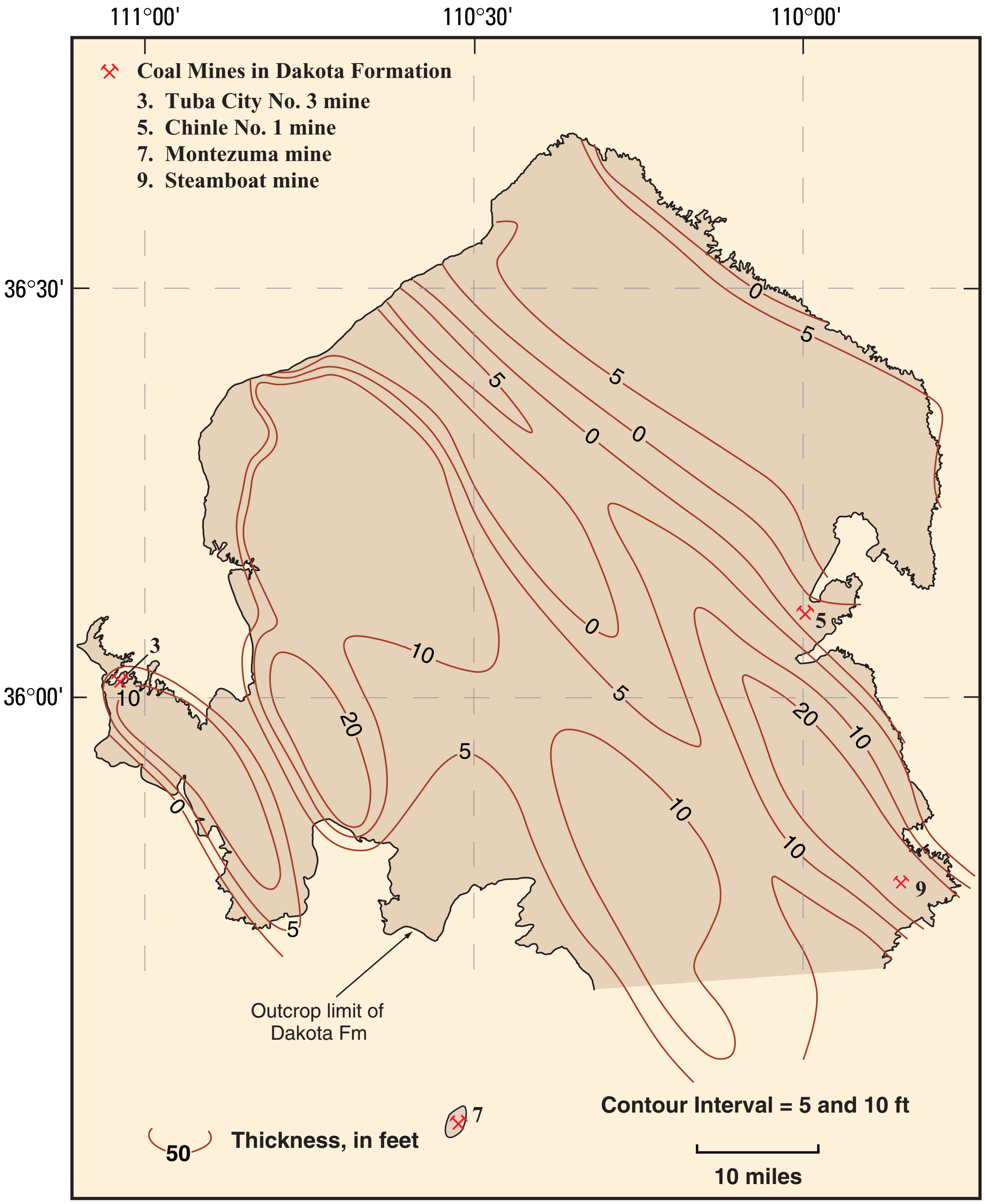

Figure 25. Isopach map of net-coal thickness in the Dakota Formation, Black Mesa, Arizona. Historic coal mines are shown.

although individual beds may not be continuous from place to place. The thickest and most extensive coal in the Toreva Formation has been mapped in the north-central part of Black Mesa. Three mines have obtained coal from the Toreva Formation, including the Keams Canyon mine, Chinle #2 mine, and the Oraibi mine, all in the southern portion of the mesa (Peirce and Wilt, 1970).

The thickness of coal in the Toreva Formation was determined from 21 measured sections, and its thickness in the basin may be interpreted from the coal isopach map (fig. 26).

Coal Distribution and Thickness in the Wepo Formation

The Wepo Formation contains the highest rank and highest quality coal on Black Mesa as well as the largest minable reserves. The coal seams are thicker, more numerous, more widespread, and more accessible for strip mining than are those in the Toreva or Dakota Formations. Coal occurs within an alternating sequence of dark olive-gray to brown siltstones and mudstones and yellowish-gray sandstones.

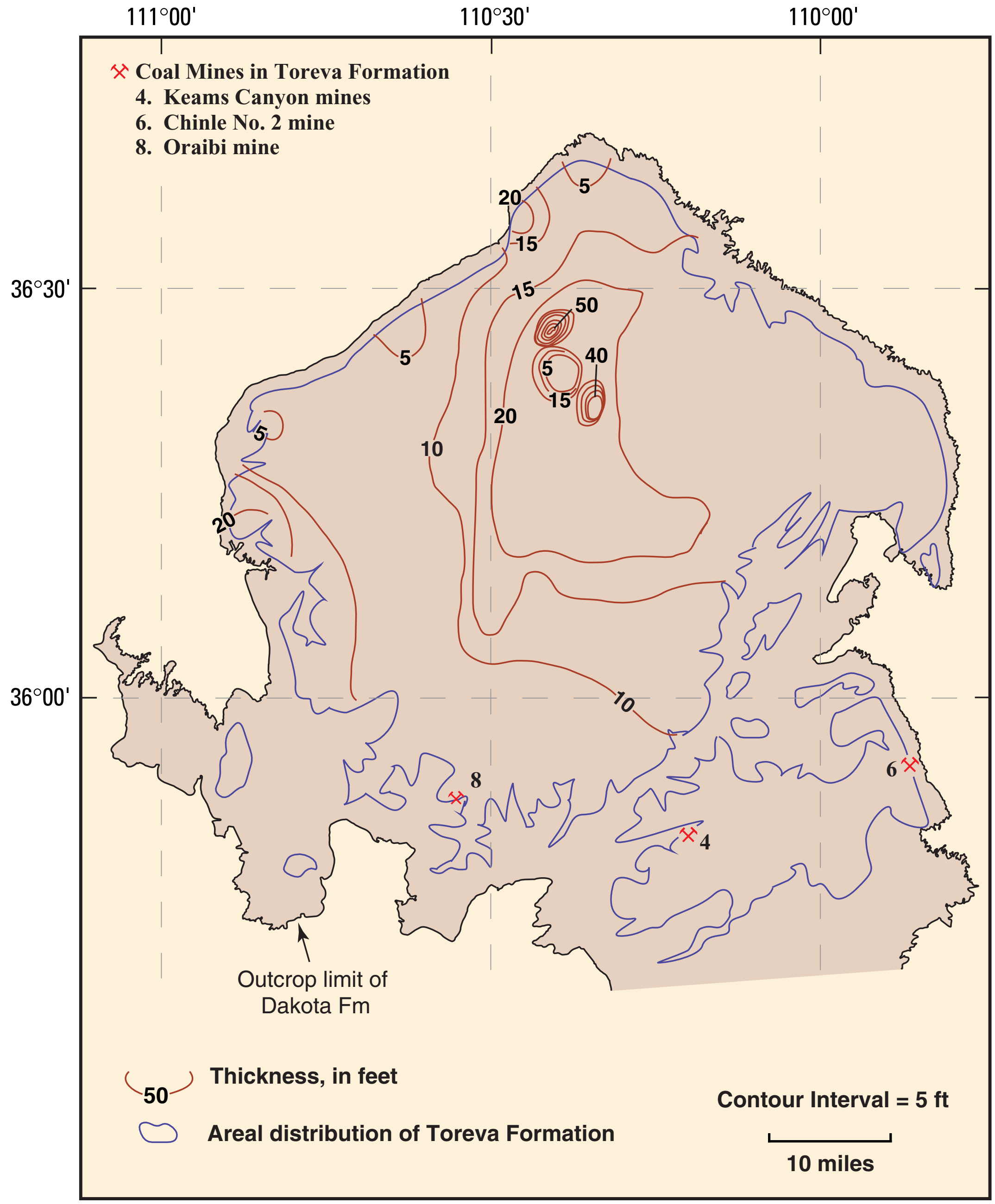

Figure 26. Isopach map of net-coal thickness in the Toreva Formation, Black Mesa, Arizona. Historic coal mines are shown.

Greater thicknesses of Wepo strata, and therefore potentially more coal, are preserved in synclines such as the Maloney and the Black Mesa synclines (figs. 7 and 27). The principal coal reserves that are being mined by the Peabody Group Coal Company (fig. 29) are associated with the Maloney syncline (fig. 7).

The Wepo contains at least 10 coal beds thicker than 3 ft in the area examined by Williams (1951) along the northwestern margin of Black Mesa in the Cow Springs area (fig. 27). The coal seams average 4 to 8 ft thick although individual seams may be from 12 to 20 ft thick (Kiersch, 1955). Individual coal seams persist for hundreds to thousands of feet but invariably thin laterally to seams a few inches to a foot thick. Because some of the coal near the surface has either been burned out, cut out locally by erosion, or covered, only a detailed drilling program can indicate the presence, thickness, and depth of coal, and provide fresh samples for testing (Peirce and Wilt, 1970).

The Wepo coal in the Black Mesa Basin occurs primarily in three areas of the northern half of Black Mesa, the Peabody

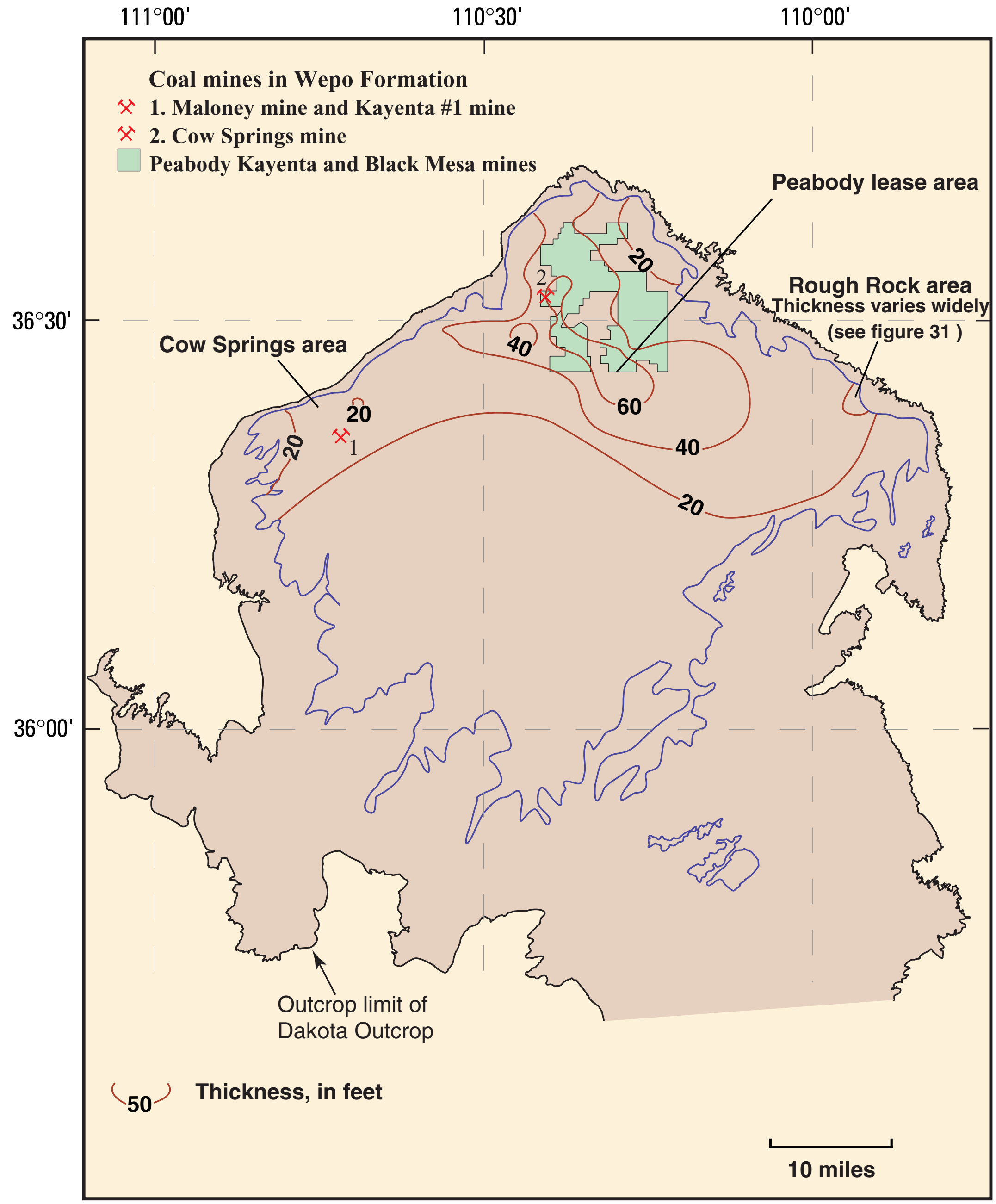

Figure 27. Isopach map of net-coal thickness in the Wepo Formation, Black Mesa, Arizona. Historic and active coal mines are shown.

lease area, the Cow Springs area, and the Rough Rock area (fig. 27). The coal thickness as shown in figure 27 was mapped as net feet of coal including intervals down to less than a foot. Data sources include sample logs from drill holes, measured sections from the CBM project, tribal water wells, and unpublished theses (fig. 4).

The largest known coal deposit occurs in the north-central part of Black Mesa and is currently being mined by the Peabody Group Coal Company (figs. 5 and 10). The coal deposits trend northwest to southeast across the lease area and appear to extend southward into the Rough Rock area (fig. 27). The coal deposit in the lease area occurs in the undifferentiated Wepo, primarily as three discontinuous deposits that total as much as 70 ft in net-coal thickness (figs. 21 and 30). The coal occurs in individual seams as thick as 20 ft to less than a foot. The coal is considered economically feasible to mine down to depths of 250 ft (R. Willson, 1995, Peabody Group Coal Company, oral commun.). The coal deposits on the Peabody Group lease thicken in the Maloney syncline that trends north-south in the northern part of the basin (fig. 7). The thicker coal appears to be preserved in the structurally low areas and to thin over

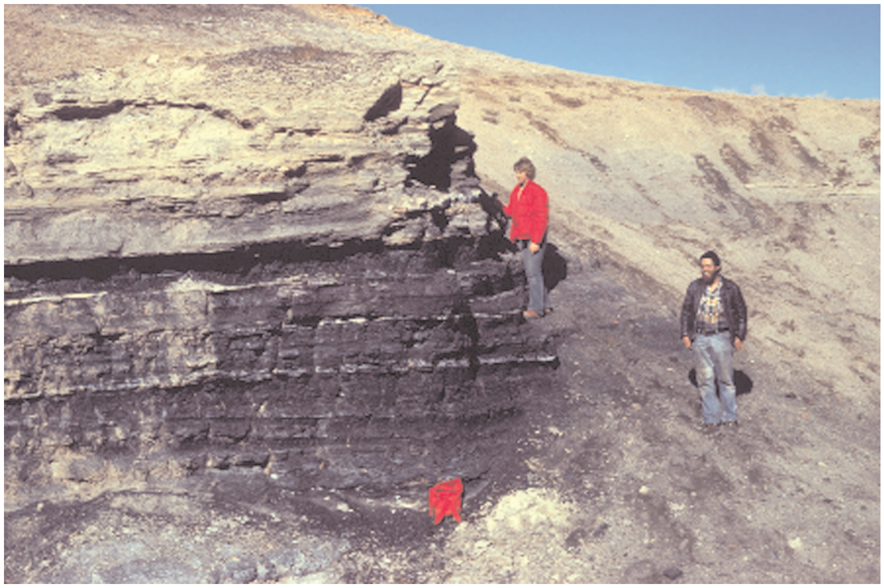

Figure 28. Coal and carbonaceous shale in Dakota Formation at Coalmine Canyon, Black Mesa, Arizona.

Figure 29. Aerial overview of the Kayenta mine, Black Mesa, Arizona with top of escarpment capped by the Yale Point Sandstone on skyline. The formation being mined is the Wepo Formation.

structurally high areas due to erosion. The average net thickness of coal is 40 ft over the Peabody Group lease, and it thins to approximately 20 ft near Rough Rock.

The Rough Rock coal deposit appears to be on the same structural and stratigraphic trends as the Peabody Group lease to the north. The area between the lease and the Rough Rock coal deposit to the southeast could be an area of future coal development. The coal deposit in the Rough Rock area covers approximately 10 mi^2 and net coal is approximately 20 ft thick (figs. 27 and 31). Figure 32 is a cross section through 20 measured sections that illustrates the facies relationships, including coal, in the upper carbonaceous member of the Wepo Formation.

The Cow Springs coal deposit averages 20 ft in thickness, but may be considerably thicker in places. Williams (1951) reported 70 net ft of coal in his measured section 14, which is approximately 6 mi to the east of the old Cow Springs Trading Post. This thickness was not confirmed during this study, but we measured a partial section of the upper Wepo at the old Tuba City No. 4 mine and observed 7 ft of net coal. The Cow Springs area in the northwestern portion of the mesa has not been mapped in detail, but its location on the Black Mesa syncline suggests that considerable coal may be preserved there (figs. 7 and 27).

Coal Quality in Black Mesa Basin

Coal Sampling and Analysis

Peirce and Wilt (1970) list 30 coal analyses found in the published literature, of which 11 were from the Wepo Forma-

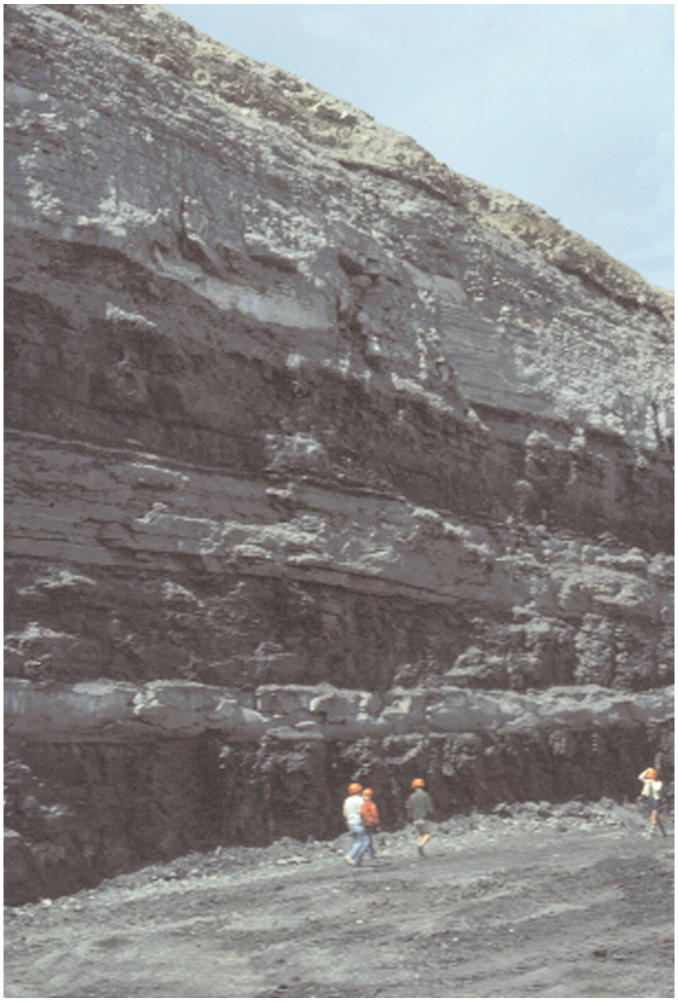

Figure 30. Working face in Kayenta mine, Black Mesa, Arizona exposing three 10-ft-thick coal beds in the Wepo Formation.

tion, 8 from the Toreva Formation, and 11 from the Dakota Formation. Moore and Swanson (1977) published analyses of 26 samples of coal from the Wepo Formation that were collected from the Peabody Group mines on Black Mesa. These data were used by Haven (1997) to determine the coal quality, coal density, and remaining coal resources in the Wepo Formation.

Fourteen new coal samples were collected during the course of this study, from the Dakota, Toreva, and Wepo Formations in measured sections and in road cuts around the mesa. The sample locations were determined by Geographic Positioning System. Peabody Group Coal Company conducted chemical analyses of these samples on a cooperative basis and provided information on the rank, ash yield, sulfur content, and calorific value. Because these analyses are on outcrop samples, their reliability may be questionable as compared to published mine-sample analyses; however, they are reported here in that they provide a measure of minimum coal quality outside the Peabody Group-leased coal areas.

Analytical Data on Coal Quality

Coal Quality in the Dakota Formation

The rank and quality of coal in the Dakota Formation in Black Mesa is known from only 15 sample analyses (table 1). Moisture, volatile matter, fixed carbon, ash, sulfur and Btu/lb have been published for 10 samples from the Tuba City No. 3 mine (Campbell and Gregory, 1911; Cooper and others, 1947; Williams, 1951; Kiersch, 1955), and one sample from the Montezuma mine (Kiersch, 1955). Four additional analyses were determined by Peabody Group on the samples collected by the CBM project.

Coal Quality in the Toreva Formation

The rank and quality of coal in the Toreva Formation in Black Mesa is known from only 10 sample analyses (table 2). Moisture, volatile matter, fixed carbon, ash, sulfur, and calorific value have been published for four samples from the Keams Canyon No. 4 mine (Cooper and others, 1947; Kiersch, 1955), three from the Chinle No. 2 mine (Kiersch, 1955), and one from the Oraibi mine (Campbell and Gregory, 1911). Two additional samples were analyzed by Peabody Group Coal Company on the samples collected by the CBM Project (table 2).

Coal Quality in the Wepo Formation

Analyses of six samples from the Wepo Formation collected from the Tuba City No. 4 mine: and five samples from the Kayenta No. 2, or Maloney, mine as summarized by Peirce and Wilt (1970) are shown in table 3. Seven analyses of channel and grab samples from the upper Cretaceous Wepo Formation, Black Mesa coal field, Navajo County, Arizona, are shown in table 4, modified from Moore and Swanson (1977). The information contained in table 4 is also available from larger published databases (Bragg and others, 1998; Affolter, chap. G, this CD-ROM). These databases contain a complete proximate/ultimate analysis and forms of sulfur and detailed trace element analyses.

The coal in the Peabody Group coal mines, located in the north-central part of the Black Mesa coal field, has been ranked as bituminous (Peirce, 1975) to subbituminous (Bragg and others, 1998). It has an average ash yield of 5.2 percent, average 12,382 Btu per pound, and average sulfur content of 0.58 percent (Peirce, 1975). The rank and quality of coal in the Wepo Formation is much better known from samples taken within the Peabody Group lease. Analytical coal quality

Figure 31. Isopach map of net-coal thickness of the Wepo Formation in the Rough Rock area shown with UTM grid for reference. Location of area within the Black Mesa Basin is shown on figure 27.

data from the Wepo Formation at the Peabody Group Kayenta and Black Mesa mines were made available to the project. Four representative analyses of samples from north to south across the north-central part of the lease are shown in table 5.

Eight additional Wepo coal samples were collected from surface outcrops by the CBM project in 1994 and were analyzed by Peabody Group Coal Company for moisture, ash, calorific value, sulfur, and rank (table 6). The samples were collected from the Photo Point section (fig. 4; northeastern Black Mesa—approximately 5 mi northwest of Chilchinbito), the Blue Gap area (fig. 4; located approximately 6 mi northeast of Blue Gap Chapter house), and the Cow Springs mine (fig. 4; approximately 5 mi east of the old Cow Springs Trading Post).

Comparison of Coal Quality with Peabody Group Lease Area

The ash and the sulfur content of coal from the Photo Point area (fig. 4) of the mesa were higher and the calorific value was lower than that of coal from the Peabody lease area. Samples from the old Cow Springs mine are higher in ash content, lower in calorific value, but the sulfur content appears to be the same as samples from the Peabody lease area. The better quality coal (high calorific value, low sulfur and ash) deposits occur in the north-central and southeastern portions of Black Mesa. The coal samples from the Blue Gap area appear to match the calorific value of Peabody Group's as-received analyses, but appear to be higher in ash and sulfur.

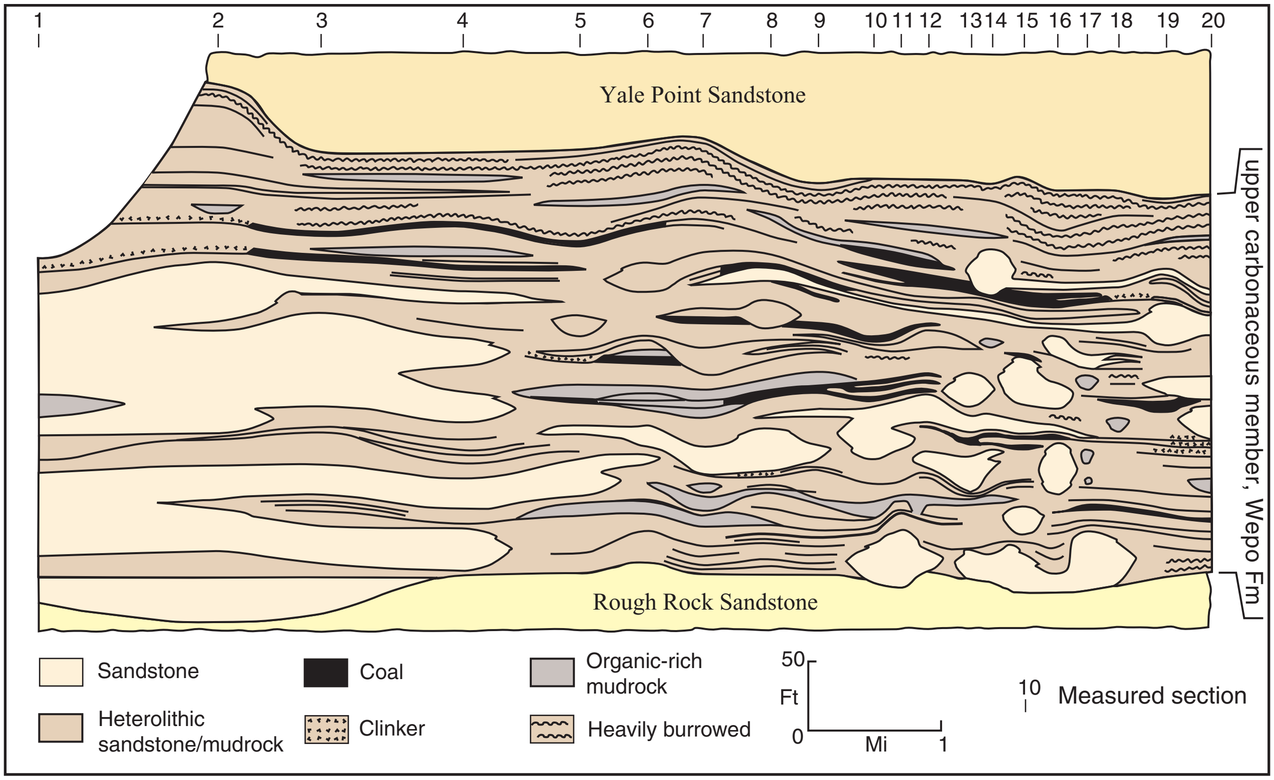

Figure 32. E.-W. stratigraphic cross section of sedimentary facies in the upper carbonaceous member of the Wepo Formation in the Rough Rock area (from Carr, 1987).

Table 1. Coal analyses from the Dakota Formation, Black Mesa, Arizona.

[Data from sources 1–4 are as compiled by Peirce and Wilt, 1970. Moisture content and volatile matter reported on an as-received basis]

Mine	Location	Moisture content (%)	Volatile matter (%)	Fixed carbon (%)	Ash content (%)	Sulfur content (%)	Btu/lb	**Original source
Tuba City	Coal Canyon	12.78	32.36	24.12	30.74	0.81	5,119	(1)
No. 3	16 mi SE. of	13.62	43.93	16.67	25.78	0.89	5,592	(1)
	Tuba City	9.15	43.59	37.23	10.03	1.70	8,837	(1)
		10.01	40.09	39.90	10.00	1.57	8,914	(1)
		11.72	41.68	33.96	12.64	2.29	7,683	(1)
		11.8	36.5	40.7	11.0	2.0	10,410	(2)
		11.8	35.8	41.1	11.3	1.8	10,270	(2)
		9.1	33.3	43.9	13.7	1.28	10,490	(3)
		9.9	31.4	44.5	14.2	-	-	(4)
		10.3	33.8	42.3	13.6	-	10,550	(4)
Montezuma	Montezuma's Chair	7.3	33.1	43.4	11.2	0.7	10,510	(1)
Outcrop	Steamboat Canyon	12.08			20.92	0.48	8,591	(5)
Outcrop	Chilchinbeto area	15.5			6.21	0.48	9,785	(5)
Outcrop	Coalmine Canyon	10.63			18.01	0.92	9,175	(5)
Outcrop	Coalmine Canyon	13.54			13.54	1.58	9,151	(5)

**Sources: (1) Kiersch (1955), p. 52, 53. (2) Cooper and others (1947), p. 32–34. (3) Campbell and Gregory (1911), p. 237. (4) Williams (1951), p. 88, 188. (5) CBM Project (1994).

Table 2. Coal Analyses from the Toreva Formation.

[Data from sources 1 and 2 are as compiled by Peirce and Wilt, 1970. Moisture content and volatile matter reported on an as-received basis. M.S., measured section]

Mine	Location	Moisture content (%)	Volatile matter (%)	Fixed carbon (%)	Ash content (%)	Sulfur content (%)	Btu/lb	**Original source
Keams Canyon No. 4	Keams Canyon	3.4	29.8	16.0	50.8	0.6	5,430	(1)
		5.3	36.8	38.9	19.0	1.1	10,270	(1)
		11.7	32.3	47.2	8.8	1.0	11,200	(2)
		11.4	32.5	45.0	11.1	0.9	10,650	(2)
Chinle No. 2	6 mi S. of Salina	5.4	37.6	42.3	14.7	1.2	10,650	(1)
		5.1	37.0	43.5	14.4	1.0	10,800	(1)
		8.62	34.31	38.87	18.20	1.30	9,807	(1)
Oraibi mine	4 mi E. of Oraibi	9.9	32.6	46.9	10.62	1.12	10,800	(1)
Outcrop	Coalmine Wash Gap M.S.	8.8			26.56	0.42	8,091	(3)
Outcrop	Blue Gap	22.3			13.39	0.62	9,858	(3)

**Sources: (1) Kiersch (1955), p. 52, 53. (2) Cooper and others (1947), p. 32–34. (3) CBM Project (1994).

Table 3. Coal Analyses from the Wepo Formation.

[Data from sources are as compiled by Peirce and Wilt, 1970. Moisture content and volatile matter reported on an as-received basis]

Mine	Location	Ref. no.	Moisture content (%)	Volatile matter (%)	Fixed carbon (%)	Ash content (%)	Sulfur content (%)	Btu/lb	**Original source
Tuba City No. 4	7 mi E. of Cow Springs	20	8.0	40.2	43.1	8.7	0.5	11,540	(1)
		21	8.4	39.7	45.2	6.7	0.4	11,830	(1)
		22	7.01	40.52	47.05	5.42	0.49	11,985	(1)
		23	10.4	37.3	45.8	6.5	0.4	11,590	(2)
		24	11.7	36.8	45.7	5.8	0.6	11,410	(2)
		25	17.4	37.0	41.6	4.0	-	10,450	(4)
Kayenta No. 2 or Maloney mine	30 mi S. of Kayenta	26	8.2	42.4	45.5	3.9	0.5	12,060	(1)
		27	8.6	38.8	48.3	4.3	0.7	11,930	(1)
		28	11.6	40.2	44.8	3.4	0.7	11,690	(2)
		29	11.5	37.5	46.9	4.1	0.9	11,660	(2)
		30	11.0	37.7	47.1	4.2	-	11,640	(3)

**Sources: (1) Kiersch (1955), p. 52, 53. (2) Cooper and others (1947), p. 32–34. (3) Williams (1951), p. 88, 188.

Table 4. Seven analyses of channel samples or grab samples from the upper Cretaceous Wepo Formation, Black Mesa Coal Field, Navajo County, Arizona.

[Modified from Moore and Swanson, 1977, their table 3. Bed designations (red, green, blue) are as used by Peabody Group Coal Company. Moisture content and volatile matter reported on an as-received basis]

Sample	Seam	Moisture (%)	Volatile matter (%)	Fixed carbon (%)	Ash (%)	Sulfur (%)	Btu/lb
D176225	Green	10.6	38.3	42.0	9.1	0.5	10,770
D176226	Green	9.3	40.8	41.4	8.5	0.5	11,100
D176227	Blue	9.3	40.1	45.3	5.3	0.4	11,560
D176231	Red	10.2	41.2	43.9	4.7	0.3	11,470
D176235	Red	8.6	40.0	42.3	9.1	0.5	10,910
D176239	Composite	10.9	37.5	44.5	7.1	0.4	10,930
D176241	Composite	21.9	31.4	39.6	7.1	0.3	9,490

Table 5. Representative coal analyses from Peabody Group Coal Company.

[R. Willson, 1994, oral commun., Peabody Group Coal Company]

	Dry basis			As-received		
	Ash (%)	Sulfur (%)	Btu/lb	Ash (%)	Sulfur (%)	Btu/lb
	6.93	0.56	12,688	6.10	0.49	11,166
	8.56	0.75	12,477	7.53	0.66	10,980
	8.87	0.47	1,2367	7.81	0.42	10,883
	9.78	0.52	12,014	8.61	0.46	10,572
Avg.	8.54	0.58	12,387	7.51	0.51	10,900

Table 6. Summary of Wepo coal quality data from CBM Project surface samples.

	Moisture (%)	Ash (%)	Btu/lb	Sulfur (%)	Rank
Samples as-received from CBM Photo Point measured section—northeastern part of mesa					
	8.24	13.48	9,723	0.95	subbituminous
	9.59	21.03	8299	0.87	subbituminous
Avg.	8.91	17.25	9011	0.91	
Samples as-received from CBM Cow Springs measured section—northwestern part of mesa					
	13.28	8.61	9709	0.52	subbituminous
	15.23	9.31	9794	0.60	subbituminous
	8.84	21.94	8502	0.65	subbituminous
	15.34	13.52	9357	0.46	subbituminous
Avg.	13.17	13.35	9341	0.56	
Samples as-received from Blue Gap area—east-central part of mesa					
	14.80	12.08	9665	0.62	subbituminous
	5.21	11.05	10838	1.75	bituminous
Avg.	10.00	11.56	10252	1.19	

Coal Resources in Black Mesa Basin

In 1909, the U.S. Geological Survey gathered data on the Black Mesa coal field and estimated that it contained 8 billion short tons of recoverable coal (Gregory and Campbell, 1911). Kiersch (1955) estimated the "minable" reserves of Black Mesa as 2 billion short tons. Averitt (1969) estimated 4 billion short tons for the inferred coal resources of Black Mesa. The Arizona Bureau of Mines estimated that as much as 21 billion short tons of coal lay beneath Black Mesa, including the Wepo coal resource as estimated at 5.65 billion short tons, the Toreva at 6.0 billion short tons, and the Dakota at 9.6 billion short tons (Peirce and Wilt, 1970). Because of the limitations of our data on coal thickness in the Dakota and Toreva Formations, this study attempted to reevaluate only the Wepo coal resources. However, improved coal volume estimates may be calculated from the coal isopach maps of the Toreva and Dakota Formations.

Coal Resources in the Wepo Formation

Haven (1997) calculated the original coal resources in the Wepo Formation of Black Mesa at 4 billion short tons, which is considerably less than the 5.6 billion short tons estimated by Peirce and Wilt (1970). The Wepo coal thickness was determined by adding all net-coal intervals in measured sections and subsurface logs, constructing an isopach map, and determining the in-place volume (Haven, 1997). A volume of 2,200,000 acre-ft was calculated from the isopach map using a program called GeoView. To determine the resources, density needed to be calculated. Haven (1997) calculated a density of 1.34 g/cm^3 based on an average ash content of 7 percent for the coal (table 4). The weight of the coal was determined to be 1,818 short tons per acre-ft. As of 1996, about 265,000,000 short tons of coal have been produced from Black Mesa resulting in a remaining resource of about 3.7 billion short tons of coal. The maximum recovery depths for the Wepo coal range from 150 ft to 250 ft on the Peabody Group lease (U.S. Office of Surface Mining, 1990). No overburden maps were constructed because of limitations of the data, but since most of the upper Wepo has been removed by erosion, much of the coal is near the surface.

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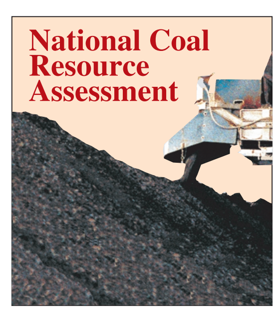

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