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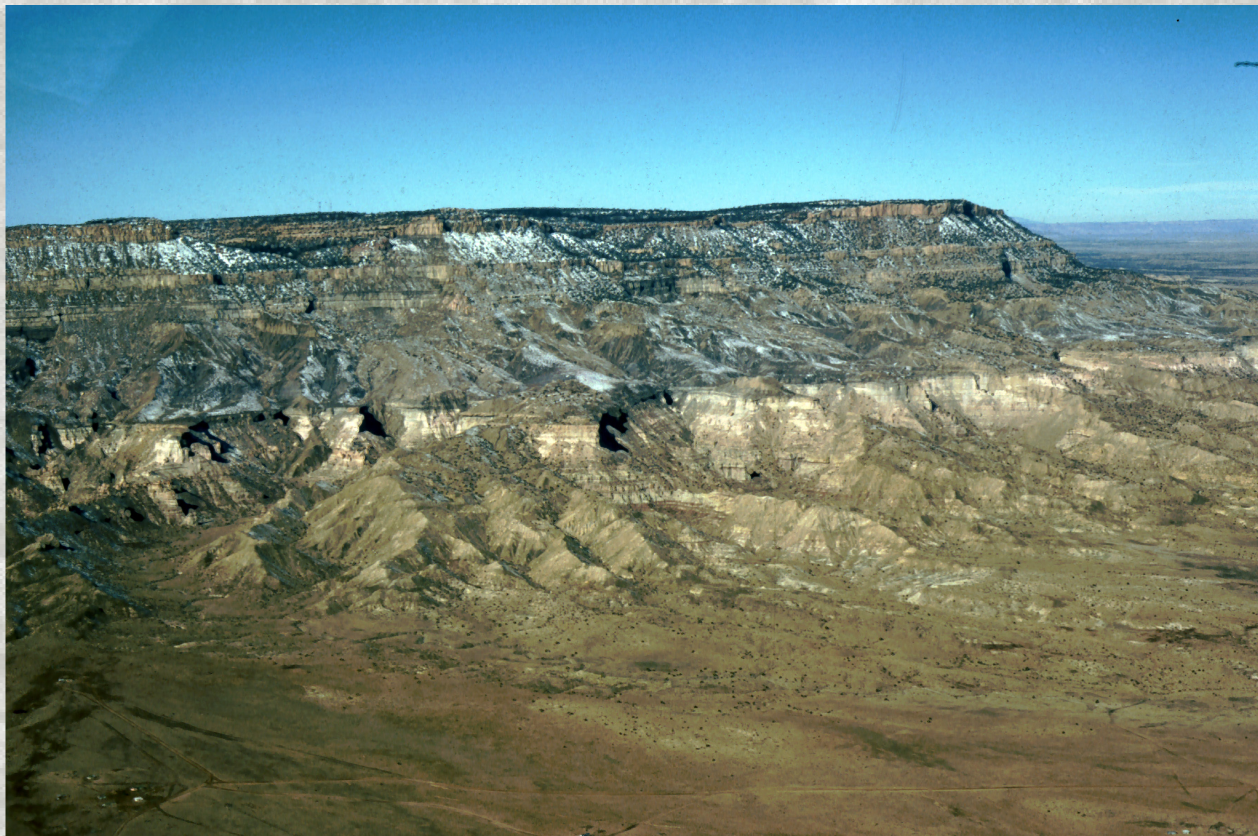

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A Brief Overview of the Cretaceous Mancos Shale in Northeastern Arizona and its Hydrocarbon Potential

by

Steven L. Rauzi
Oil and Gas Program Administrator
&
Jon E. Spencer
Senior Geologist

Arizona Geological Survey
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Arizona Geological Survey
416 W. Congress St., #100
Tucson, AZ 85701

Introduction

The recent development of horizontal drilling techniques and application of hydraulic fracturing to horizontal wells has dramatically increased oil and gas production in the U.S., notably in areas where extensive organic-rich shale and calcareous shale deposits are present. Shale and limestone formations that contain hydrocarbons without sufficient porosity and permeability to yield oil and gas with conventional drilling techniques are being reconsidered in light of these technological advances. The Mancos Shale in the San Juan Basin in northwestern New Mexico has become a target of interest because the new technologies have unlocked the potential of unconventional resource plays like the Mancos Shale. Broadhead (2013) described the Mancos Shale oil and Mancos Shale gas plays in New Mexico at the San Juan Basin Energy Conference on March 18-19, 2013. In this report we briefly review the geology of the Mancos Shale in Arizona and consider its potential to yield hydrocarbons with horizontal drilling and hydraulic fracturing.

Upper Cretaceous Mancos Shale

Late Cretaceous subsidence in the interior of the North American continent resulted in flooding of a vast area to form an inland seaway (McGookey et al., 1972). The Upper Cretaceous Mancos Shale, deposited in northeastern Arizona near the southwestern margin of the inland seaway, thickens to the east toward the interior of the inland seaway. The thick Mancos Shale sequence at its type locality in the San Juan Basin of northwestern New Mexico reflects its more interior position in the inland seaway (Page and Repenning, 1958; O'Sullivan et al., 1972; Young, 1973).

Black Mesa, a remnant of Cretaceous strata in northeastern Arizona, is coincident with, and the namesake for, the Black Mesa Basin. The Mancos Shale of Black Mesa represents a southwestward-extending tongue of the Mancos of the type locality at Mancos, Colorado, and represents only a minor part of the type section (Repenning and Page, 1956). Repenning and Page (1956) point out that the Mancos Shale of Black Mesa is in an intermediate position between the Mancos at the type locality and its pinch-out near Show Low, Arizona.

The marine Mancos Shale in Arizona is almost entirely restricted to Black Mesa on the Navajo and Hopi Indian Reservations (Fig. 1), where it rests on Dakota Sandstone. The Mancos Shale consists of calcareous shale with upward-increasing silt and fine sand, and is Cenomanian to Turonian in age (Nations et al., 2000). It was divided into four informal members by Kirkland (1983), as follows: (1) fossiliferous shale that grades upward from lower, silty, brown, non-calcareous shale into dark gray calcareous shale, (2) dark gray calcareous shale that is fissile where less calcareous and blocky where more calcareous, (3) interbedded fine-grained calcareous sandstone, siltstone, and shale, and (4) non-calcareous shale and siltstone. Young

(1973) described the lower shale unit of the Mancos in the Black Mesa Basin as consisting of medium-dark-gray to nearly black shale interbedded with thin layers of fine sandstone.

Thickness of the Mancos Shale is about 220 m (722 ft) on the north side of Black Mesa, thinning to about 145 m (475 ft) to the south (Nations, 1989). Depth to the base of the Mancos Shale ranges from about 1,500 ft on the north side of Black Mesa to about 100 ft to the south (Fig. 2). Table 1 lists available well logs, cuttings, and core for oil and gas wells used in determining depths represented by contours in Figure 2. Depth is greater in the northern part of Black Mesa than in the southern part partly because of greater erosion in the south. Structural uplift of the Mogollon Slope to the south has removed most of the Cretaceous Wepo Formation and all of the Cretaceous Yale Point Sandstone in southern Black Mesa (Fig. 3).

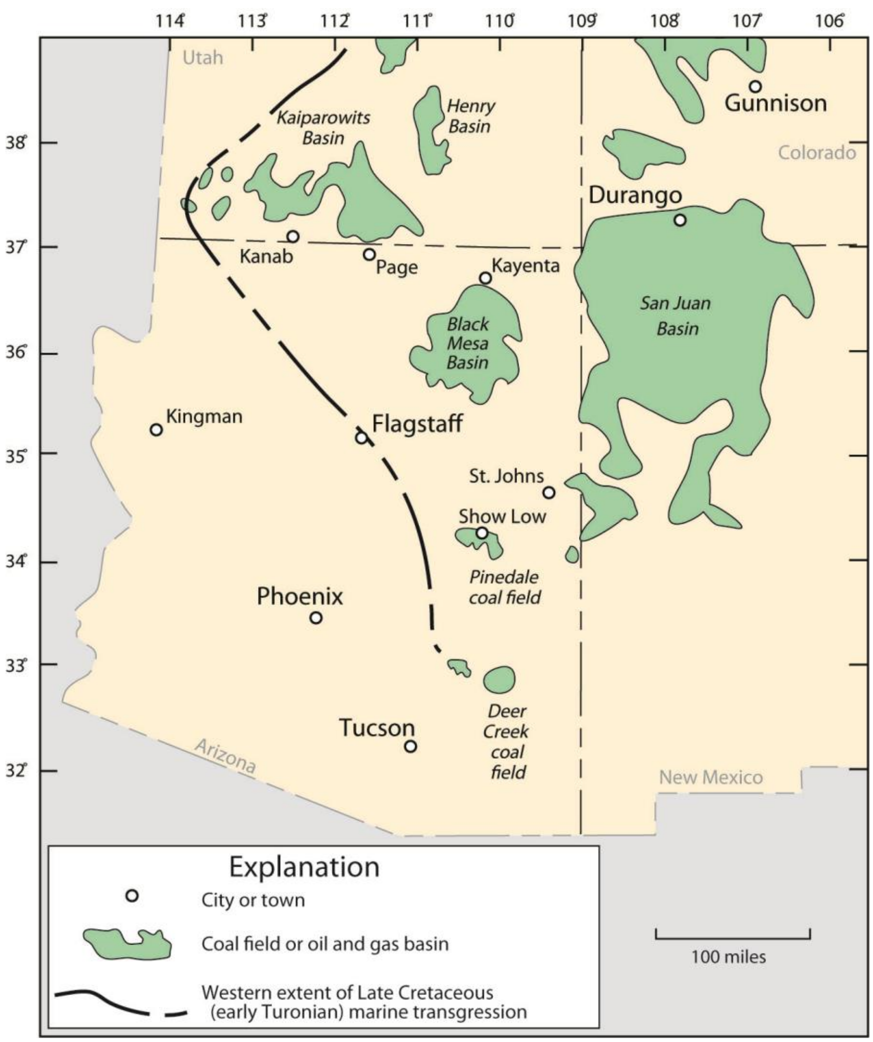

Figure 1. Map of Cretaceous basins in the Colorado Plateau region, showing the location of the Black Mesa Basin. Black Mesa is underlain by the Cretaceous Mancos Shale, but the shale is eroded from surrounding areas rather than being thicker at Black Mesa (from Nations et al., 2000).

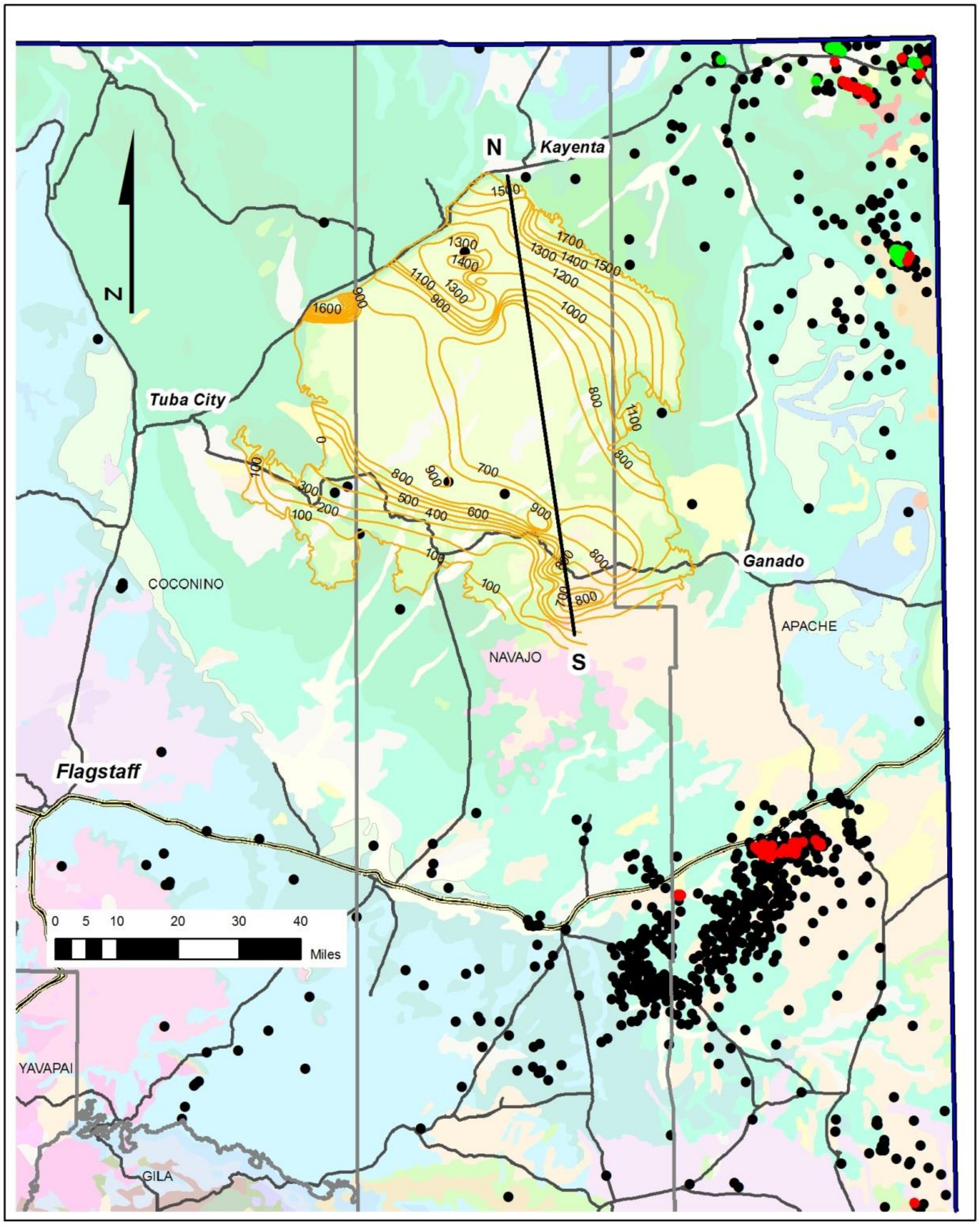

Figure 2. Map showing depth to the base of the Mancos Shale and top of the Dakota Sandstone in Black Mesa Basin of northeastern Arizona. Contour interval is 100 ft. Contours are based on (1) depths determined from oil and gas wells (see Table 1), (2) outcrop exposures around the perimeter of the basin, and (3) water-well depths [data sets (2) and (3) were provided by J.D. Nations (2011)]. See Fig. 3 for north-south cross section. Dots represent exploration wells drilled for oil and gas; red dots represent wells completed for natural gas, helium, or CO_2; green dots represent wells completed for oil.

Table 1. Available Well Logs and Samples in the Black Mesa Basin (Well ID is Permit #)

Well ID	Depth (ft)	Log type

Texaco 1 Hopi-A nw nw 15-26n-16e, Permit 307**:** Drilled 5/1965, TD 5915 ft Precambrian metamorphic, Triassic Kayenta at surface; Sample number 1366: cuttings 0-5870; core chips 5830-5906.

0307AMST	0-5906	Graphic Lithologic Log # D-2573
0307IEL	1002-5919	Induction Electrical Log
0307SL	70-5918	Sonic Log-Gamma Ray with Caliper

***Skelly 1 Hopi-A** sw ne 35-30n-17e, Permit 309: Drilled 5/1965, TD 7780 ft Precambrian granite, Mancos Shale 400-918 ft; Sample number 1355: cuttings 200-2700 and 2800-7780; no core chips.

0309AMST	200-7780	Graphic Lithologic Log # D-2597
0309GRN	50-7783	Gamma Ray-Neutron Log
0309IEL	1989-7783	Induction Electrical Log
0309SL	1990-7781	Sonic Log with Caliper

***Amerada 1 Hopi** se ne 08-29n-19e, Permit 310: Drilled 5/1965, TD 7750 ft Precambrian granite, Mancos Shale 302-821 ft; Sample number 1370: cuttings 0-7750; no core chips.

0310AMST	0-7750	Graphic Lithologic Log # D-2592
0310BHCS	1220-7748	Borehole Compensated Sonic Log
0310GRN	50-7749	Gamma Ray-Neutron Log
0310IEL	1220-7750	Induction Electrical Log

Atlantic Refining 9-1 Hopi sw se 09-28n-15e, Permit 312: Drilled 7/1965, TD 6640 ft Precambrian granite, Jurassic Navajo at surface; Sample number 1358: cuttings 10-6640; no core chips.

0312AMST	0-6640	Graphic Lithologic Log # D-2550
0312BHCS	1037-6641	Borehole Compensated Sonic Log
0312CDL	1037-6642	Compensated Formation Density Log
0312GRN	100-6640	Gamma Ray-Neutron Log
0312IEL	1037-6640	Induction Electrical Log
0312ML	2800-6640	Micro Log with Caliper

Moore Moore Miller 1 Hopi nw nw 06-29n-15e, Permit 321: Drilled 10/1965, TD 6998 ft Precambrian metamorphic, Jurassic Navajo at surface; Sample number 1797: cuttings 1000-6998; no core chips.

0321AMST	1000-7000	Graphic Lithologic Log # D-2559
0321FT	3408-6682	Formation Tester
0321IEL	993-6999	Induction Electrical Log
0321SL	993-6998	Sonic Log-Gamma Ray with Caliper

Pennzoil 1-11 Hopi nw nw 11-29n-14e, Permit 474: Drilled 12/1968, TD 6940 ft Precambrian granite, Jurassic Navajo at surface; Sample number 1457: cuttings 0-6940; no core.

0474AMST	0-6940	Graphic Lithologic Log # D-3166
0474BHCS	904-6943	Borehole Compensated Sonic Log
0474GRN	0-6944	Gamma Ray-Neutron Log
0474IEL	904-6944	Induction Electrical Log

***R.Y. Walker & Petrofunds 1 Navajo** se sw 20-36n-18e, Permit 574/580: Drilled 12/1971, TD 1270 ft Cretaceous Dakota, Mancos Shale 620-1255 ft; Sample number 1694: cuttings 580-1244; no core.

0574CAL	207-1254	Caliper Log
0574GRN	207-1257	Gamma Ray-Neutron Log
0574IEL	207-1256	Induction Electrical Log

***** Wells with Mancos Shale samples at the AZGS

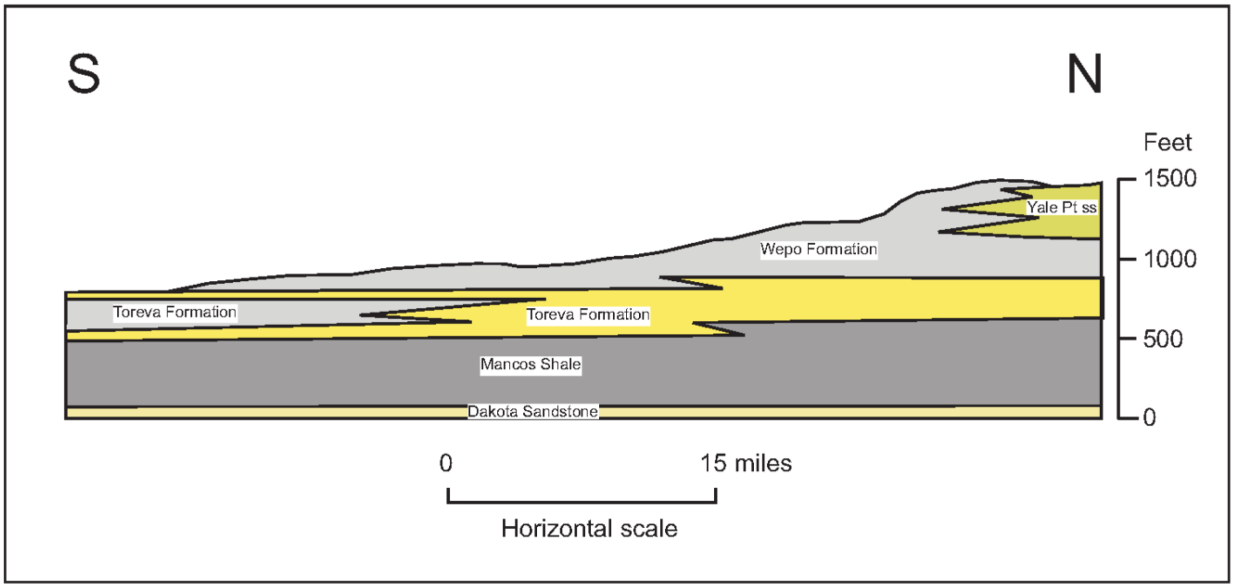

Figure 3. Diagrammatic south-north section showing stratigraphic relations of Cretaceous rocks on Black Mesa (From Repenning and Page, 1956). See Fig. 2 for location of section.

Hydrocarbon potential

Repenning and Page (1956) considered the Late Cretaceous coastal plain from the present San Juan Basin in northwestern New Mexico across the Black Mesa area to be the site of approximately uniform deposition until latest Cretaceous time. Laramide uplift of the Mogollon Highlands across central Arizona shifted deposition away from the Black Mesa area and toward the San Juan Basin area. During this time, the youngest Late Cretaceous deposits in the Black Mesa Basin area were eroded and re-deposited in the San Juan Basin (Repenning and Page, 1956) and in other basins in southern Utah (Nations et al, 1985). Late Oligocene to early Miocene extensional collapse of the Basin and Range Province in southern and western Arizona eliminated southwestern sources of clastic debris and resulted in a transition from deposition to erosion in the Black Mesa area (Nations et al., 1985; Potochnik, 2001; Cather et al., 2008; Flowers et al., 2008; Dickinson et al., 2010). The absence of Paleocene or Eocene strata in the Black Mesa Basin, and their presence in both the San Juan Basin and the Uinta Basin in east-central Utah, suggest that the Black Mesa Basin area was uplifted and subjected to erosion coincident with the Laramide uplift of the Mogollon Highlands in central Arizona (Nations et al., 1985). This suggests that the burial depth of the Cretaceous strata in the Black Mesa Basin was less than in the San Juan Basin, which contains more than 3,500 ft of Paleocene and Eocene strata (Baltz, 1967). This is in addition to a considerably thicker Cretaceous section than is present in Black Mesa Basin (Peterson and Kirk, 1977). No thermal maturation data or direct indicators of burial depth are known for the Cretaceous Mancos Shale in Black Mesa Basin.

Tucker (1983) investigated the correlation of crude oils and potential source rocks in northeastern Arizona but did not sample Cretaceous strata in her study. There are no known geochemical analyses of the nearly black lower shale and other shale units of the Mancos Shale at Black Mesa, and their Total Organic Carbon (TOC) content is not known. Sampling and geochemical analysis of the dark shale units is essential to understanding the shale-gas potential of Mancos Shale in Arizona and would provide important information about the depth of burial and thermal maturation. The dark shale units of the Mancos Shale in Black Mesa Basin, and known productivity of dark Mancos Shale in nearby San Juan Basin, suggest that TOC content of Mancos Shale is significant in Black Mesa Basin and could be a potential source of hydrocarbons using new drilling and production technology. However, this inference has not yet been tested

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