

Definition and Hydrocarbon Potential of the Late Devonian Three Forks Formation, Williston Basin, South Dakota*

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Abstract

An evaluation of the Three Forks Formation, to determine hydrocarbon potential, was performed in the Williston Basin of South Dakota using well logs from the South Dakota Geological Survey. Basin analysis included identification of upper and lower boundaries, extent, lithologic description, stratigraphic correlation, and hydrocarbon potential. Thickness of Three Forks rocks ranges from 0 to 170 feet, and was thickest in northern Perkins and Corson counties and thinned toward the basin margins. Lithologically, the rocks consisted primarily of interbedded shale and dolomitic limestone. Stratigraphically, Three Forks rocks occurred between the underlying Birdbear Formation and overlying Englewood Formation. In areas where the Englewood was absent, it was overlain by the Lodgepole Formation. In North Dakota, eastern Montana, and Canada, the Three Forks underlies the Bakken Formation, serving as a reservoir for Bakken shale oil. No Bakken rocks were identified in well logs from South Dakota and the Three Forks and other Late Devonian formations have been underexplored. Well log analysis revealed three previously unidentified potential subsurface structures in the Williston Basin of South Dakota. In addition, data have supported proposed southeastern extensions of the Cedar Creek Anticline and Sheep Mountain Syncline. Black shale, indicating areas of restricted water circulation, have been identified in the Three Forks, in limited areas of estimated maturity, that suggest ideal conditions for the preservation of organic matter. These areas were correlated using gamma-ray spikes and estimated TOC values from 1.4 to 5.6 wt. %, at depths Three Forks rocks would be expected to contain mature hydrocarbons. Based on estimated TOC values and associated thicknesses of TOC-bearing intervals, limited potential exists for Three Forks source and reservoir rock in northwestern South Dakota, particularly in northern Perkins and eastern Harding counties.

Introduction

The Late Devonian Three Forks Formation, in the Williston Basin, has received renewed attention as an oil reservoir for the Bakken Petroleum System in North Dakota, Montana, and Canada. There, the Three Forks is overlain by the Bakken Formation, whose organic-rich black shale is the hydrocarbon source for the Three Forks reservoir (Nordeng, 2009). It was hypothesized that the Three Forks is present in the Williston Basin of South Dakota and that the Bakken is absent. This interval has not been previously explored and if the Bakken is absent, the petroleum

potential of the Three Forks could be source-limited. The study area consisted of the southern portion of the Williston Basin, located in South Dakota ([Figure 1](#)). To date, in South Dakota, the Red River Formation is the most productive geologic unit for oil and no production from Devonian formations has occurred.

Regional Geologic Setting

The northern Great Plains region, and Williston Basin, overlies Precambrian basement terrane. Periods of continuous and intermittent deposition and erosion occurred in the basin throughout the Paleozoic. During the Late Devonian, the basin was located on a broad shelf along the western margin of Laurentia. The region was tectonically active during the Late Devonian as the Antler Orogeny commenced, prior to Three Forks time, along the Cordilleran Geosyncline to the west. Collisional tectonics induced subsidence throughout the basin and the resulting compressive forces were responsible for the activation of structural elements and reverse faulting in the area (Sandberg and Mapel, 1967).

Stratigraphy and Lithology

The Three Forks Formation in the Williston Basin of South Dakota unconformably overlies the Birdbear Formation and unconformably underlies the Englewood Formation or Lodgepole Formation, where the Englewood is absent. The Bakken Formation was not present in any wells located in South Dakota. The Three Forks ranges in thickness from 0 to 170 ft (51.8 m), attaining maximum thickness in north-central Corson County. Gradually thinning towards the basin margins, the Three Forks pinches out prior to reaching the basins extent. In the central portion of the basin in South Dakota, the Three Forks primarily consists of black-dark gray shale with interbedded white-light gray limestone and dolomitic limestone. Near the margins of the basin, the Three Forks primarily consists of green-gray dolomitic limestone with interbedded blue-green, green-gray, and maroon shale. Thus, from the central basin to the margins, the Three Forks transitioned from a euxinic to transitional near-shore marine environment.

Structural Interpretation

The extent of the Williston Basin in South Dakota is identified by a combination of structural and depositional boundaries depending on location and time interval during the Late Devonian. The uplifted Transcontinental Arch structurally limited Three Forks deposition to the south and southeast, while the eastern extent was depositional. The uplifted Cedar Creek Anticline and Black Hills Arch provided western and southwestern barriers to Three Forks deposition, respectively. Although the Three Forks was likely not deposited along the extent of the Cedar Creek Anticline, it was deposited in the Sheep Mountain Syncline to the west.

Substantial thickness changes occur in Corson County in the area of a proposed anticline. This is interpreted as a possible anticline with two depositional sub-basins off the western and eastern flanks. The anticline was likely a submarine high, allowing Three Forks deposition along its extent, with sediments thickening in the sub-basins. Erosion affected the topography after regression of Birdbear seas and prior to Three Forks deposition, resulting in depositional highs and lows, especially near the margins of the basin. An alternate interpretation of this area is the

possible southeastward extension of the Nesson Anticline (Sandberg and Mapel, 1967; Baars, 1972). Either way, activation of the anticline during Three Forks time could be responsible for thickening of the sediments in the sub-basins off its western and eastern flanks.

The Three Forks is shallowest at -1356 ft (-413 m) in central Stanley County and deepest at -5360 ft (-1634 m) in northeastern Harding County. The Three Forks is absent along the Cedar Creek Anticline and in an area on the upthrown block of the Cedar Creek Fault. A southeastward extension of the Cedar Creek Anticline, following the trend of the Cedar Creek Fault is proposed. The Cedar Creek Fault is a normal fault, with the Late Devonian section (with the exception of the Souris River Formation, which does not extend that far south) preserved on the downthrown (eastern) block. On the upthrown block to the west, only the Englewood Formation is present and it unconformably overlies the Ordovician Red River Formation. Deposition of the Three Forks along the Sheep Mountain Syncline is interpreted to be a southwestern extension of the Three Forks Sea around the uplifted Cedar Creek Anticline. A southeastward extension of the Sheep Mountain Syncline into northern Butte County is also proposed, based on the presence of the Three Forks Formation. Two previously unidentified subsurface structures are located to the east of the Cedar Creek Anticline in north-central Harding County. The proposed syncline is northeast of the South Cave Hills Syncline, while the proposed anticline is further eastward and may be a northwestern extension of the Slim Buttes Anticline to the southeast.

Hydrocarbon Potential

Basic petrophysics of the Three Forks Formation in the Williston Basin of South Dakota was determined from well logs and limited pyrolysis results. Resistivity and sonic logs were used to estimate total organic carbon (TOC) in wells with hypothesized hydrocarbon potential via the $\Delta \log R$ technique (Passey et al., 1990). As estimated from the $\Delta \log R$ technique, TOC values ranged from 1.4 to 4.4 wt. % in Perkins County and from 1.4 to 5.6 wt. % in Harding County. Pyrolysis results from a well in north-central Perkins County indicate 2% TOC for the Upper to Middle Three Forks and 0.99% for the Middle to Lower Three Forks. Estimated TOC values for this well were 1.4 wt. % in the Lower Three Forks and 2 to 2.6 wt. % in the Upper Three Forks.

Conclusions

The Williston Basin subsided throughout the Late Devonian, but the Antler Orogeny, commencing prior to Three Forks deposition and persisting through the Early Mississippian, brought about many structural changes within the basin. The Cedar Creek Anticline was uplifted during Three Forks time and the Cedar Creek Fault was activated. An isolated seaway connection to the northwest provided the only deposition of the Three Forks west of the anticline and fault. This seaway followed the north-northwest trend of the Sheep Mountain Syncline.

A proposed anticline located in Corson County, and possibly extended into northern Dewey County, is likely either an isolated uplift or a southeastward extension of the Nesson Anticline in North Dakota. During Three Forks deposition, this anticline was below sea level with two deeper sub-basins off its western and eastern flanks. This anticline also appears to be the southeastward extent of the east-west trending structural high that divided the Williston Basin into northern and southern regions during the latest Devonian and earliest Mississippian. Division of the basin during this time prevented the Bakken Formation from being deposited in South Dakota, while a westward transgression deposited the Englewood Formation instead.

Analysis of Late Devonian strata indicates a potential syncline and anticline in north-central Harding County. The proposed anticline may be the northwestern extension of the Slim Buttes Anticline to the southeast. In addition, southeastward extensions of the Cedar Creek Anticline and Sheep Mountain Syncline have been proposed. The extension of the Cedar Creek Anticline is thought to follow the extent of the Cedar Creek Fault to the southeast and is based on the absence of Late Devonian strata (with the exception of the latest Devonian/earliest Mississippian Englewood Formation). The proposed extension of the anticline coincides with previous work done by Sandberg and Mapel (1967) and Baars (1972). The southeastward extension of the Sheep Mountain Syncline is based on the presence of the Three Forks Formation extending into northern Butte County.

This work has defined the boundaries of the Late Devonian Three Forks Formation in the Williston Basin of South Dakota, proposed the presence of previously unidentified subsurface structures, and estimated the formations' hydrocarbon potential. Further work is needed to properly identify the extent and nature of these subsurface structures and to provide a more thorough determination of hydrocarbon potential. However, due to the lack of wells in the area, this likely cannot be accomplished without additional wells being drilled and/or seismic surveys.

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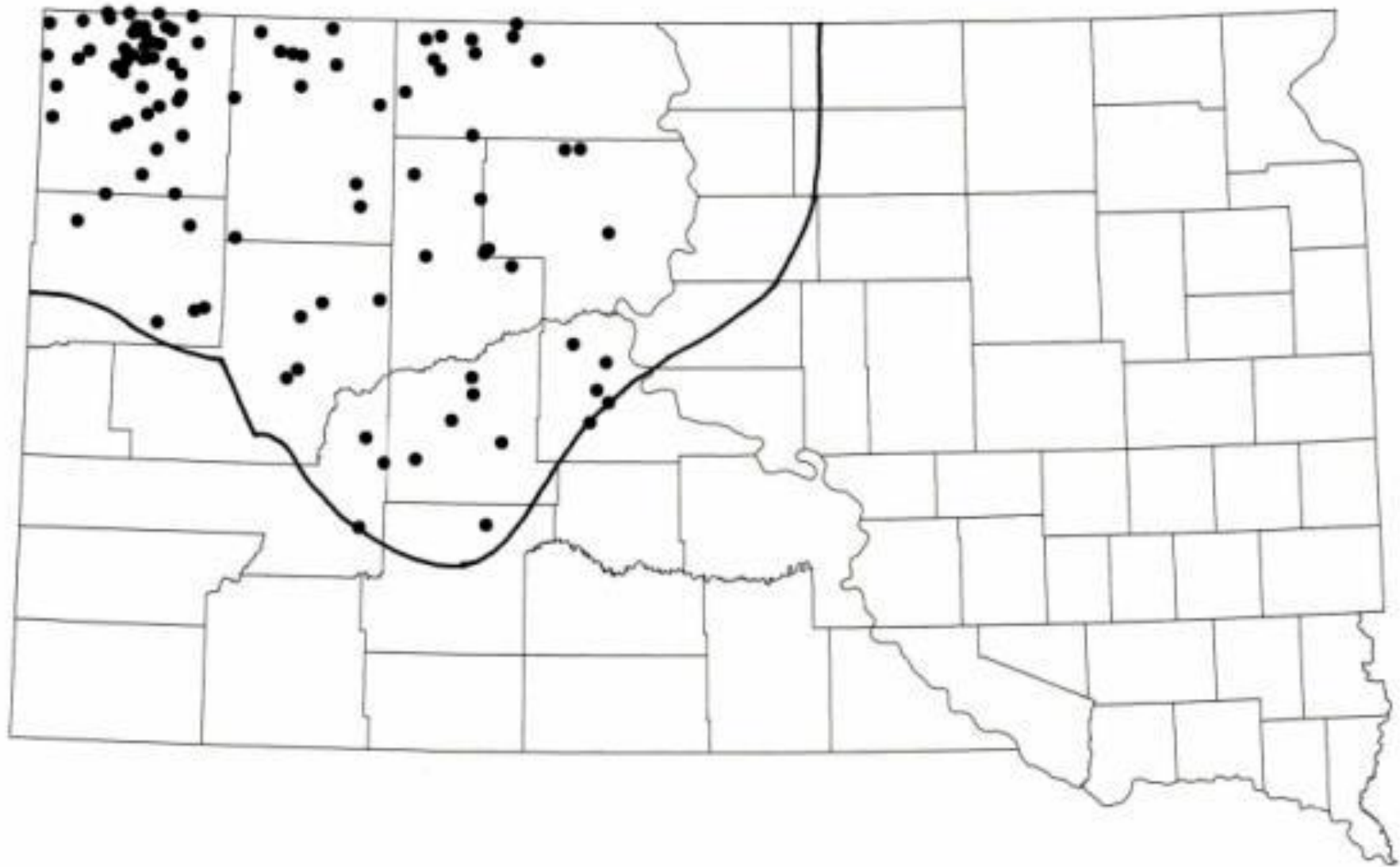


Figure 1. Study area in South Dakota illustrating the southern portion of the Williston Basin (outlined in black). Wells utilized in the analysis are represented by the black circles. Map scale 1:10,000,000.