

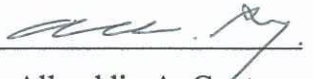
SEQUENCE STRATIGRAPHY AND MICROFACIES ANALYSIS OF THE
LATE DEVONIAN THREE FORKS FORMATION, WILLISTON BASIN,
NORTH DAKOTA AND MONTANA, U.S.A.


by
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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the degree of Master of Science (Geology).

Golden, Colorado

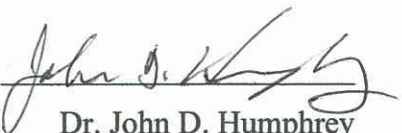
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ABSTRACT

The Late Devonian Three Forks Formation is well known as a potential reservoir rock within the Bakken petroleum system. A better knowledge of the sequence stratigraphy and microfacies will contribute to an understanding of the regional extent, distribution, and detail reservoir rock properties of this formation. Cores from 21 wells were described in detail and 11 lithofacies are recognized in the Three Forks Formation. These 11 lithofacies are: A: argillaceous mosaic anhydrite, B: thinly-bedded reddish silty claystone and anhydrite beds and nodules, C: thinly-bedded reddish-greenish silty claystone and anhydrite beds and nodules, D: structureless to faintly-laminated dolomitic greenish silty claystone with occasional anhydrite beds and nodules, E: structureless-faintly laminated reddish silty claystone with scattered granule-sized lithoclasts, F: structureless-faintly laminated greenish claystone with scattered granule-sized lithoclasts, G: chaotic greenish silty claystone and dolomitic siltstone, H: very thinly-bedded greenish claystone and dolomitic siltstone, I: structureless to ripple cross-laminated dolomitic siltstone, J: bioturbated dolomitic sandy siltstone, , and K: burrowed silty very fine-grained sandstone (Sanish Member). Five facies associations were interpreted from the 11 lithofacies and grouped by depositional environment. They are, from top to bottom: FA1: upper supratidal sabkha, FA2: lower supratidal sabkha, FA3: upper intertidal mud flat, FA4: lower intertidal mud flat, and FA5: open marine. The lower and middle part of the Three Forks Formation are dominated by supratidal sabkha deposits, whereas, the upper part is dominated by the intertidal and occasional open marine deposits. Nine microfacies types have been recognized from the 11 lithofacies and categorized based on their textural, structural, and compositional properties, these are: M1: mosaic felted anhydrite, M2: laminated to bedded anhydritic-dolomitic silty claystone, M3: silty dolomitic claystone, M4: chaotic-brecciated dolomitic siltstone, M5: laminated to ripple-laminated silty dolostone, M6: structureless to laminated dolomitic claystone, M7: silty anhydritic dolostone, M8: laminated clayey dolostone, and M9: dolomitic siltstone. Authigenic dolomite, anhydrite, and pyrite along with illite and chlorite clay cementation are the main diagenetic features in the Three Forks.

Key stratigraphic surfaces are recognized from the core data and traceable throughout the study area in well log data. These major stratigraphic surfaces are the Type 2 sequence boundary at the base of the Three Forks, Type 1 sequence boundary at the top of the Three Forks, and a transgressive surface in the middle part of the Three Forks. Six 4th order parasequence sets have been identified and two systems tracts are interpreted, which include the lowstand systems tract and transgressive systems tract. The Three Forks Formation shows an overall deepening upward succession with prograding and retrograding stacking patterns that resemble the 3rd order lowstand and transgressive systems tracts. Correlation using integrated core and well log data has resulted in the development of a stratigraphic evolution model that depicts the sequence stratigraphic framework of the Three Forks Formation in the study area, and can be useful for further hydrocarbon exploration and development activities of this formation in the Williston Basin.

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DEDICATION

For my parents, my sisters, and my fiancée Siti Nurlaela.

CHAPTER 1

INTRODUCTION

The Late Devonian Three Forks Formation is well known as one of the potential hydrocarbon reservoir rocks within the Bakken petroleum system in the Williston Basin. This formation consists of eleven main lithofacies and two of these lithofacies (facies C and D of Berwick, 2008; facies G and H of this study) are locally present as reservoir rocks. Lateral distribution, vertical variation, depositional environment changes, stratal stacking pattern and thickness variation of this formation are still not well understood regionally. Increased understanding of the stratigraphy, especially the sequence stratigraphic framework, along with lithofacies and microfacies analysis will be very important and helpful in generating a better understanding of the overall Bakken petroleum system.

1.1 Research Objectives and Purposes

The purpose of this research is to provide analysis and interpretation of the Three Forks Formation lithofacies and microfacies in a sequence stratigraphic framework. Knowledge about sequence stratigraphy can provide useful information about the overall depositional history and evolution of this formation. Detailed analysis and interpretation of lithofacies and microfacies of this formation may provide useful information about the mineralogy, texture, and diagenetic history within each depositional setting that can be applied in future petroleum exploration efforts.

The objectives of this research are to:

- (1) understand the lateral and vertical facies variation within the Three Forks Formation;
- (2) establish microfacies analysis and interpretation of the Three Forks Formation;
- (3) interpret and understand the diagenetic features within the Three Forks Formation; and

- (4) develop conceptual models for the stratigraphic evolution of the Three Forks Formation based on the sequence stratigraphic concept.

1.2 Research Contributions

Contributions of this research are as follow:

- (1) recognition of various lithofacies and facies associations along with their depositional settings within the Three Forks Formation;
- (2) establishment and linkage the lithofacies laterally and vertically;
- (3) establishment of detailed analysis of the microfacies for recognition of potential reservoir properties based on mineralogical and textural data;
- (4) identification of various diagenetic features, paragenetic sequences, and their impact to the reservoir rock properties;
- (5) recognition of of 5th order (high order), 4th order (medium order), and 3rd (low order) stratigraphic cycles in the Three Forks Formation; and
- (6) development of sequence stratigraphic framework and evolution model for the Three Forks Formation.

1.3 Location of Study Area

The study area is the North Dakota and Montana part of the Williston Basin (Figure 1). The stratigraphic interval for this research is the Late Devonian Three Forks Formation. Subsurface cores and well log data will provide the data needed for this study, as this formation is almost entirely present in the subsurface.

1.4 Previous Works

There are only a few articles that focus on the Three Forks Formation, and which add to the overall understanding about its stratigraphy, facies, depositional environments, mineralogy and diagenetic history.

The overview of the geology of Williston Basin by Sandberg et al. (1958), Kerr (1988), and Gerhard et al. (1990) give a brief description of the Three Forks and Bakken formations.

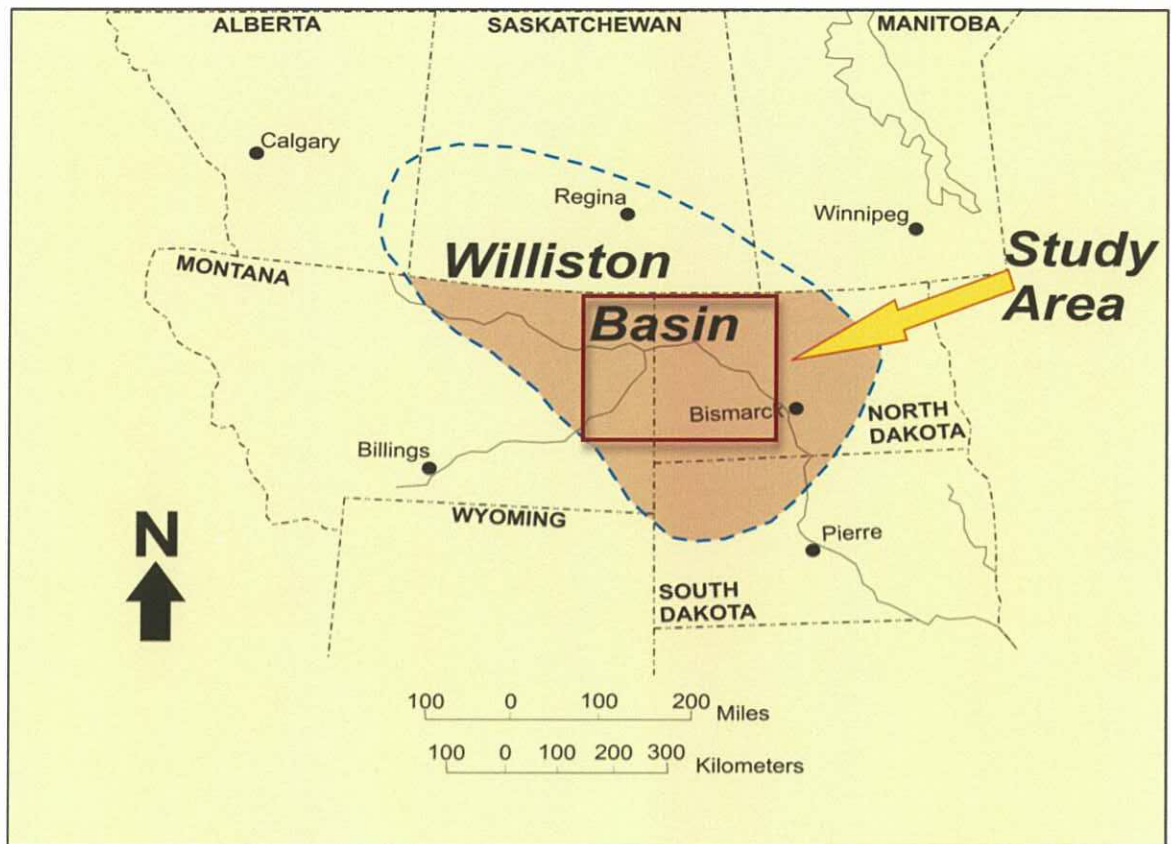


Figure 1.1 Location of study area (map modified from Pitman et al., 2001)

Meissner (1978) discussed the petroleum geology of the Bakken Formation. He described the stratigraphy, reservoir properties, geochemical (source rock) properties, petrophysical properties, and theories on localized fracturing of the Bakken Formation and associated units.

Smith et al. (2000) interpret the base of the Bakken Formation to be a sequence boundary (marine flooding surface). Their study showed that the lower Bakken Shale rests unconformably on the truncated surface of the Three Forks Formation.

Dumonceaux (1984) described the facies variation and depositional environments and their controlling factors. She recognized four different facies in the Three Forks Formation, and those facies were deposited in supralittoral/supratidal (dolomicrite facies), littoral/intertidal (argillaceous micrite and micrite facies), low-energy sublittoral/subtidal environments (argillaceous biomicrite and micrite facies), and land/sabkha (argillaceous dolomicrite facies) (Figure 1.2). Based on the occurrence of anhydrite, she interpreted that the Three Forks Formation to have been deposited in an arid climate condition. She also concludes that the repeated transgressions and regressions during the Late Devonian caused the lateral migration of environments and produced the complex mosaic of lithofacies.

Berwick (2008) is an excellent reconnaissance interpretation of the upper Three Forks Formation. He interprets five different lithofacies (A, B, C, D, and E facies from bottom to top) in the upper part of the Three Forks Formation. Mineralogical analysis was conducted using XRD and SEM-EDS, and he identified variation in detrital and authigenic minerals. His interpretation of depositional environments for the upper Three Forks Formation is similar to Dumonceaux (1984), and ranges from coastal plain sabkha (facies A), saline tidal flat (facies B and facies C), supratidal and intertidal (facies D), and lower shoreface (facies E) environments (Figure 1.3). From the sequence stratigraphy interpretation, he recognized some major stratigraphic surfaces, such as the angular unconformity on top of the Sanish Member or base of the lower Bakken Shale, a marine flooding surface at the same stratigraphic position, flooding surfaces at the base of the fourth facies (facies D), and a bounding discontinuity at the base of the third facies (facies C). From his cross sections, the upper Three Forks Formation is thinning and truncated towards the basin margin: to the north (Figure 1.4). He also concluded that the

upper Three Forks Formation was deposited in arid climate condition.

This research will study the Three Forks Formation sedimentology and stratigraphy sub-regionally in the North Dakota and Montana portion of the Williston Basin using both studies by Berwick (2008) and Dumonceaux (1984) as a basic framework for the sedimentological aspect of this formation.

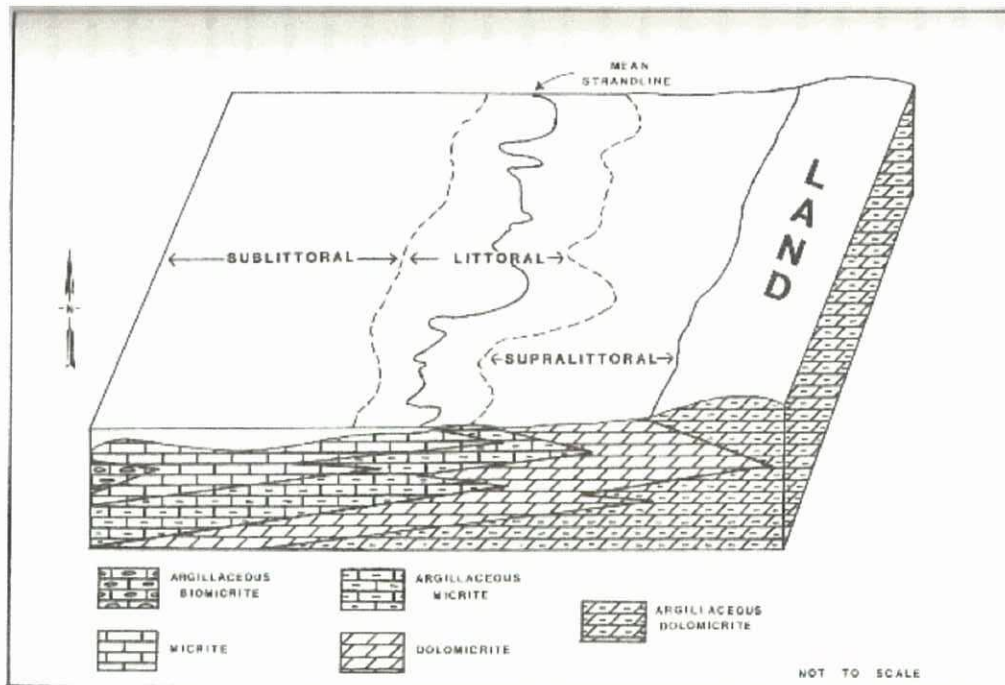


Figure 1.2 Diagram illustrate the depositional setting model for the Three Forks Formation (Dumonceaux, 1984).

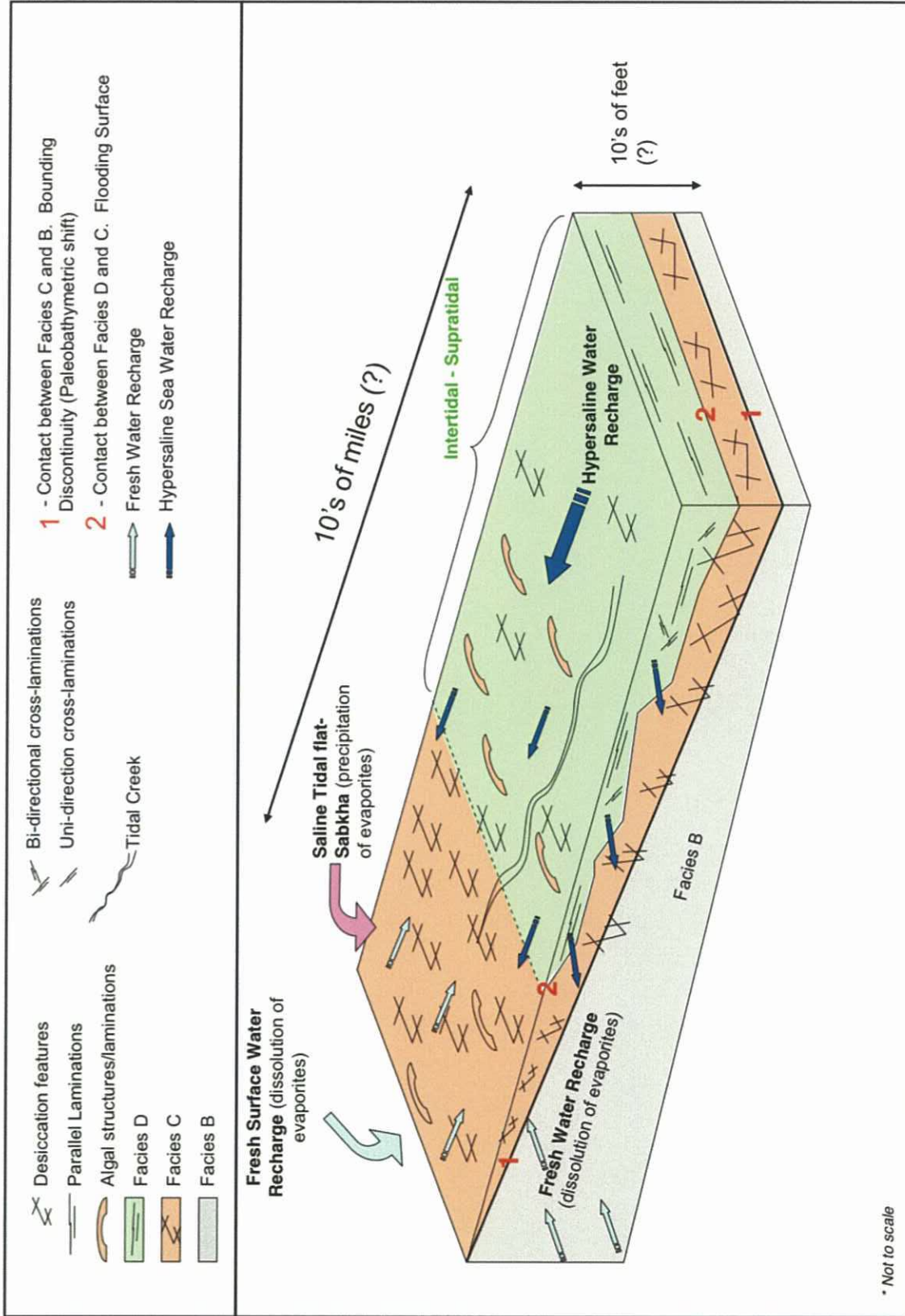


Figure 1.3 Diagram illustrate the depositional setting for the Upper Three Forks Formation (Berwick, 2008).

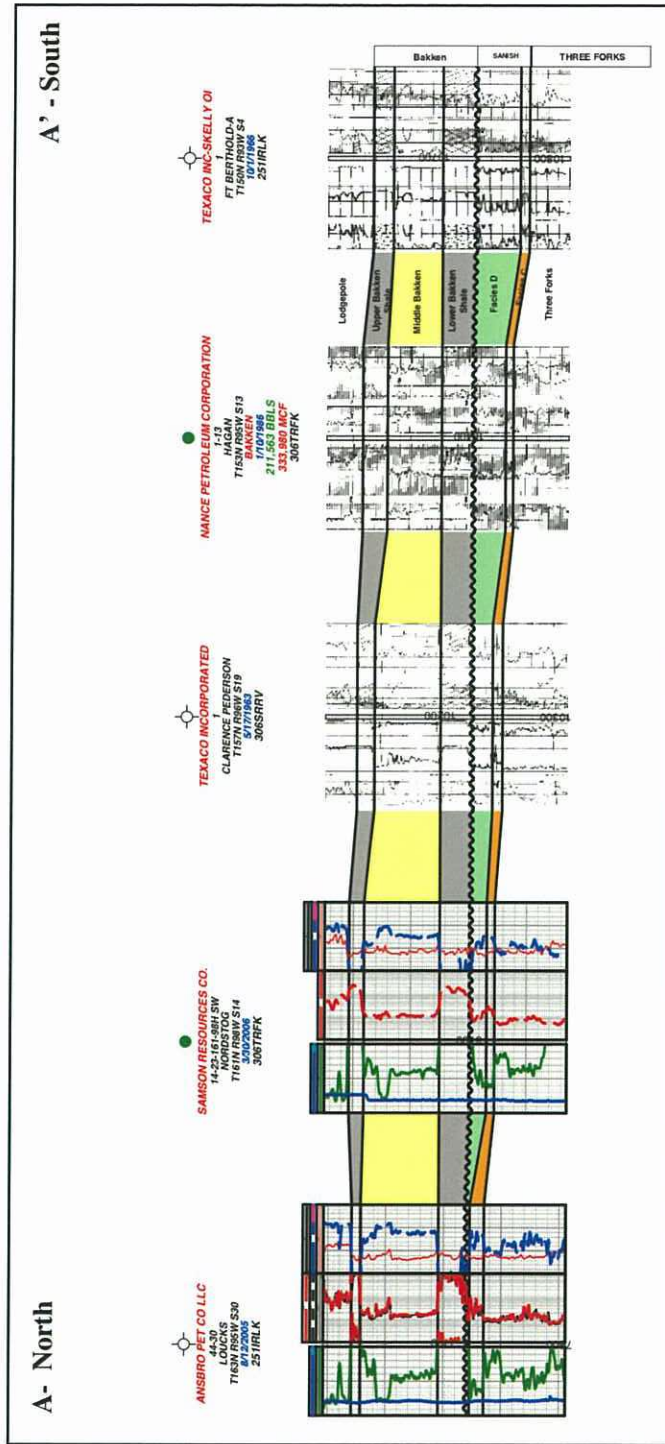


Figure 1.4 North – south stratigraphic cross section showing the thinning Upper Three Forks Formation strata to the North towards the basin margin (Berwick, 2008).